HYBRID RYE MAY PARTIALLY OR FULLY REPLACE CORN IN DIETS FED TO GROWING OR REPRODUCING SWINE

BY

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DISSERTATION

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Abstract

Eight experiments were conducted to test the hypothesis that hybrid rye may replace corn in diets for gestating and lactating sows, weanling and nursery pigs, and growing-finishing pigs without negatively impacting growth performance. In experiment 1, 45 sows per treatment were fed diets in which 0, 25, 50, or 75% of corn was replaced with hybrid rye in corn-soybean meal control diets formulated for gestation or lactation. Results indicated no differences in average daily feed intake (ADFI) or average daily gain (ADG) among treatments in gestation, but sows fed greater amounts of hybrid rye in lactation weaned heavier litters (quadratic, $P < 0.05$) with greater numbers of weaned offspring (quadratic, $P < 0.05$). Individual pig weights were not influenced by diet, but pre-weaning pig mortality tended to be reduced (quadratic, $P < 0.10$) from sows fed diets with hybrid rye. Based on the observation that sow gestation ADFI and ADG were not influenced by hybrid rye inclusion in the first experiment, experiment 2 was conducted to test the hypothesis that the metabolizable energy (ME) in hybrid rye is not different from corn when fed to gestating sows. Results indicated that the ME of hybrid rye was less ($P < 0.05$) than of corn, but the difference was less pronounced than values previously determined in growing pigs, likely due to greater fermentative capacity of sows. Experiments 3 and 4 were conducted to test the hypothesis that feed preference and growth performance of pigs will not differ when hybrid rye replaces portions of corn in nursery diets. In a two-way choice experiment, pigs preferred ($P < 0.05$) a corn-based diet 56.6% of the time and a diet in which 50% of corn was substituted with hybrid rye 43.4% of the time. In experiment 4, pigs were fed diets with up to 30, 40, and 100% replacement of corn with hybrid rye in phase 1 (day 1 to 7), phase 2 (day 7 to 21), and phase 3 (day 21 to 34) diets, respectively. Results indicated no differences in average body weight or ADG during the experiment, but ADFI increased (quadratic, $P < 0.05$) with greater inclusion of

hybrid rye in the diet in phase 3 and for the overall period. Consequently, gain:feed (G:F) was reduced (quadratic, $P < 0.05$) in phase 3 and overall as well. The incidence of diarrhea was reduced (quadratic, $P < 0.05$) for pigs fed diets containing 6 or 9% hybrid rye in phase 1. As hybrid rye inclusion in the diets increased, neutrophils decreased and then increased (quadratic; day 21, $P < 0.10$; day 34, $P < 0.05$), and blood urea N increased (day 21, quadratic, $P < 0.05$; day 34, linear, $P < 0.05$). Because no negative effects on growth performance were observed in phases 1 and 2 of experiment 4, experiment 5 was conducted to test the hypothesis that greater quantities of hybrid rye may be included at the expense of corn in nursery diets without impacting growth performance. Indeed, replacing up to 60% of corn with hybrid rye in phase 1 and up to 90% in phase 2 did not result in diminished performance of weanling pigs. Average daily gain and ADFI increased (linear, $P < 0.05$) with greater inclusion of hybrid rye in the diet in phase 1, and in phase 3, when up to 100% of corn was replaced with hybrid rye, body weights and ADG of pigs did not differ among treatments. Pigs consumed more feed (quadratic, $P < 0.05$) in phase 3 and overall, and thus G:F was reduced (quadratic, $P < 0.05$). Differences (quadratic, $P < 0.05$) in concentrations of cytokines on day 35 indicate that pigs fed hybrid rye experienced a greater degree of inflammation, but no differences in fecal scores or incidence of diarrhea were observed, and more importantly, growth was not affected. Experiments 6 and 7 were conducted to test the hypothesis that feed preference and growth performance of pigs will not be different when corn is replaced with hybrid rye in diets for growing pigs. In the two-way choice experiment, pigs preferred ($P < 0.05$) the diet containing corn as the exclusive cereal grain 83.4% of the time versus the diet containing hybrid rye as the exclusive cereal grain. Pigs in experiment 7 had a tendency for reduced ADFI (linear, $P < 0.05$) as the replacement rate of hybrid rye in the diet increased (0, 33, 66, or 100%). Nevertheless, final body weight on day 27 of the experiment did not differ among treatments, nor did ADG or G:F, indicating hybrid rye was well-utilized by growing pigs. Experiment 8 was conducted to test the hypothesis that substituting hybrid rye in place of corn in diets for growing-finishing pigs would not influence growth performance or carcass traits of pigs. Within each of the 3 dietary phases, 0, 33, 66, or 100% of corn was replaced with hybrid rye. Results indicated that growth performance of pigs fed hybrid rye was suppressed in phase 1, as ADG and ADFI were less (linear, $P < 0.05$) and day 35 body weight tended to be reduced (linear, $P < 0.05$) for pigs fed greater amounts of hybrid rye. However, pigs compensated in later phases, resulting in no difference in body weights among treatments on day 70 or 97. A tendency for reduced (linear, $P < 0.10$) ADFI emerged in the late finisher phase, which also resulted in a tendency for reduced ADG in the final phase of the experiment. Overall, ADG, ADFI, and G:F were not different among treatments for the entirety of the experimental period (day 1 to 97). Most carcass traits, including hot carcass weight, carcass yield, 10th rib fat thickness, loin eye area, and fat free lean percent, were not different among treatments, but loins of pigs fed hybrid rye had lighter visual color (linear, $P < 0.05$) and lighter backfat instrumental color (linear, $P < 0.05$). Pigs fed greater amounts of hybrid rye had heavier organs (linear, $P < 0.05$), including heart, kidney, liver, and empty gastrointestinal tracts, likely as a result of the need to handle greater total N and dietary fiber from hybrid rye compared with corn. In conclusion, hybrid rye may replace up to 75% of corn in diets for gestating and lactating sows without influencing performance, and lactation performance may be improved when 17 to 34% inclusion rate of hybrid rye is fed. Nursery pigs and growing pigs prefer diets based on corn to diets containing hybrid rye when given the choice. Hybrid rye may replace up to 60% of corn in diets in the first week after weaning, up to 90% of corn in week 2 and 3 post-weaning, and up to 100% of corn in week 4 and 5 post-

weaning without impacting ADG. Average daily feed intake of growing pigs may be limited upon introduction to hybrid rye, but overall, the ingredient is well-utilized by growing and finishing pigs. Hybrid rye may replace up to 100% of the corn in diets for finishing pigs without influencing most carcass traits, although organ weights will be expected to be heavier for pigs fed greater inclusion of hybrid rye.

Key words: cereal grains, corn, growth performance, hybrid rye, pig, sow

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CHAPTER 1: Introduction

Despite accounting for less than 1% of worldwide cereal grain production (FAO, 2018), rye has a nutritional composition suitable for being a high quality feed ingredient for pigs, and its agronomic characteristics are superior to other cereals in certain growing environments (Geiger and Miedaner, 1999, Jørgensen et al., 2007; Geiger and Miedaner, 2009; Schittenhelm et al., 2013; Laidig et al., 2017). Historically, rye has not been used in diets for pigs in large amounts due to concerns of ergot contamination, antinutritional factors truncating growth, and poor palatability (Wilson and Wright, 1932; Friend and MacIntyre, 1969; Antoniou et al., 1981). However, varieties of hybrid rye developed in recent years in Germany have reduced susceptibility of ergot contamination, increased grain yield, and better overall plant hardiness (Geiger and Miedaner, 1999; 2009; Miedaner and Geiger, 2015); thus, interest in producing rye has grown not only in Europe, but in North America as well. Compared with corn, hybrid rye contains similar amounts of standardized ileal digestible amino acids and standardized total tract digestible P (McGhee and Stein, 2018; 2019). Like other cereal grains, hybrid rye contains large amounts of highly digestible starch, which provides substantial energy to the pig (McGhee and Stein, 2018; 2020). Hybrid rye contains more fermentable dietary fiber than wheat, corn, and sorghum (McGhee and Stein, 2020), which may confer health benefits to pigs as well (May et al., 1994; Karppinen et al., 2003; Le Gall et al., 2009; Bach Knudsen et al., 2005; 2016; 2017; Zhao et al., 2013). Nutrient composition and digestibility of energy and nutrients in hybrid rye fed to growing pigs have been reported (Strang et al., 2016; McGhee and Stein, 2018; 2019; 2020), and results of recent research indicate that hybrid rye may replace portions of barley or wheat without impeding growth of nursery pigs (Chuppava et al., 2020; Ellner et al., 2020; Wilke et al., 2020), growing-finishing pigs (Schwarz et al., 2015; 2016; Bussières, 2018; Smit et al., 2019), and sows (Sørensen and Nymand, 2017). However, corn is the dominant cereal grain fed to pigs in many parts of the world, including the United States, and a gap in knowledge exists for the effects of substituting hybrid rye for corn in diets for pigs. Therefore, a series of experiments were conducted to test the hypothesis that hybrid rye may replace corn in diets for gestating and lactating sows, weanling pigs, and growing-finishing pigs without negatively impacting growth performance. It was also the objective of this research to test the hypothesis that feeding hybrid rye to pigs will alter blood immune parameters and give an indication of inflammatory immune response and overall health status.

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CHAPTER 2: Hybrid rye for pigs: Literature review

Abbreviations

ADG	average daily gain
ADFI	average daily feed intake
AID	apparent ileal digestibility
ATTD	apparent total tract digestibility
CFU	colony forming units
G:F	gain:feed
ME	metabolizable energy
SID	standardized ileal digestibility
STTD	standardized total tract digestibility

Introduction

Production and agronomic characteristics of hybrid rye

Hybrid rye is a crop that was originally developed in Germany on the basis of maximizing heterosis by breeding 2 genetically different, inbred lines of rye to produce a superior F1 hybrid (Geiger and Miedaner, 2009; Miedaner et al., 2014). The crop exhibits an average of 20% greater yield than conventional open-pollinated varieties of rye, and hybrid rye can also out-yield other small grains when managed correctly (Geiger and Miedaner, 1999, Jørgensen et al., 2007; Geiger and Miedaner, 2009; Hübner et al., 2013; Schittenhelm et al., 2013; Laidig et al., 2017).

Because of the nature of hybrid breeding, the F1 generation of hybrid seed is more genetically uniform than open-pollinated varieties, which results in more uniform fields with synchronized flowering and pollination windows (Geiger and Miedaner, 1999, 2009; Miedaner and Geiger, 2015). Besides grain and whole plant yield, selection for disease and lodging resistance are also important breeding goals when developing parent lines (Geiger and Miedaner, 1999; Miedaner et al., 2019). Rye is hardy against abiotic stress, including drought, low temperatures, and soil conditions unfavorable for growing other crops (e.g., sandy or acidic), and newly developed hybrid varieties of rye also have reduced risk of ergot contamination (Miedaner and Geiger, 2015; Miedaner and Laidig, 2019).

Rye is not currently harvested in large quantities in North America, but open-pollinated rye is often used as an over-wintering cover crop (Teasdale, 1996; Krueger et al., 2011; Miedaner and Laidig, 2019). In Europe, however, rye is commonly grown and harvested for its use in traditional rye bread, as a feed ingredient for livestock, and as a substrate for biofuel production (Miedaner et al., 2010; Haffke et al., 2014). European countries have had access to hybrid rye since the 1980s, and over 80% of rye grown in Germany is from hybrid varieties (Laidig et al., 2017), but hybrid rye has only been available in Canada and the United States since 2014 and 2016, respectively. The potential market for hybrid rye in North America is largely comprised of whiskey distilleries and the livestock feed industry, and with its agronomic advantages to open-pollinated rye and some other small grains, North American production of hybrid rye is expected to increase.

Chemical composition

As a small grain, rye has a similar composition to barley, wheat, and triticale. The dry matter of ground hybrid rye is usually 87 – 90%, and the concentration of gross energy is approximately 3,850 kcal/kg on an as-is basis (Strang et al., 2016; McGhee and Stein, 2018). The starchy endosperm constitutes more than half of the hybrid rye grain by weight, although hybrid rye contains slightly less starch than wheat, but more starch than barley (Schwarz et al., 2015; Strang et al., 2016; McGhee and Stein, 2018; 2020; Linina et al., 2019). Hybrid rye contains between 12 and 18% total dietary fiber, of which 1 to 4% is soluble dietary fiber (Strang et al., 2016; McGhee and Stein, 2018; 2020). Fiber in rye is distributed throughout the outer pericarp, middle aleurone layer, and inner endosperm, and the composition and fermentability varies significantly depending on the location of the fiber in the grain (Glitsø et al., 1998; 1999). Arabinoxylan, cellulose, mixed-linked β-glucans, fructooligosaccharides, and lignin are the primary constituents of the fiber in hybrid rye (Jürgens et al., 2012; Strang et al., 2016; McGhee and Stein, 2018).

Hybrid rye has less lipid content than most other grains, including barley, wheat, corn, and sorghum, and the acid-hydrolyzed ether extract concentration in rye is less than 2% (McGhee and Stein, 2018). The concentration of crude protein in hybrid rye ranges from 8 to 13% (Strang et al., 2016; McGhee and Stein, 2018, 2020; Smit et al., 2019), although the amount of N in the grain depends on the genotype of the variety as well as growing conditions and N fertilization application (Fowler et al., 1990; Jürgens et al., 2012; Miedaner et al., 2014). The average concentration of Lys in hybrid rye is 0.35%, and Met, Thr, and Trp concentrations are approximately 0.15%, 0.30%, and 0.10%, respectively (Strang et al., 2016; McGhee and Stein, 2018). The ash content of hybrid rye is approximately 1.5%, of which 15 to 20% is P (McGhee and Stein, 2019; Smit et al., 2019). Hybrid rye contains approximately 0.30% P by weight, which is close to the amount of P in barley, wheat, corn, and sorghum, although the majority of P in hybrid rye and other cereal grains is bound to phytic acid (McGhee and Stein, 2019). Practically devoid of Ca (0.05% or less), hybrid rye is similar to other cereal grains in that regard as well (McGhee and Stein, 2019; Smit et al., 2019).

Digestibility of nutrients and energy in pigs

The digestibility of nutrients and energy in hybrid rye by growing pigs was determined and compared with other cereal grains in a series of experiments conducted at the Swine Research

Center at the University of Illinois from 2017 to 2019 (McGhee and Stein, 2018; 2019; 2020). The standardized ileal digestibility (**SID**) of crude protein and most amino acids, including Lys, Met, Thr, and Trp is less than the SID of amino acids in other cereal grains, including dehulled barley, wheat, corn, and sorghum. In hybrid rye, the SID of crude protein is approximately 75%, and the SID of Lys is approximately 65%, with some variation dependent on the hybrid variety (Strang et al., 2016; McGhee and Stein, 2018). Because hybrid rye contains more total amino acids than corn, however, concentrations of standardized ileal digestible crude protein and most amino acids in hybrid rye are generally not different from corn (McGhee and Stein, 2018).

Non-heat-treated hybrid rye has substantial intrinsic phytase activity – over 2,000 phytase units of phytase activity is present in hybrid rye compared with less than 70 phytase units of phytase activity in corn (McGhee and Stein, 2019). Due to the intrinsic phytase activity, the standardized total tract digestibility (**STTD**) of P is greater in hybrid rye than in corn when microbial phytase is not included in the diet. Microbial phytase inclusion in the diet increases the STTD of P in all cereal grains, and this is true for hybrid rye as well; however, the magnitude of the increase in P digestibility elicited by microbial phytase differs among grains (McGhee and Stein, 2019). Therefore, when microbial phytase is used, the STTD of P does not differ among hybrid rye, barley, wheat, and corn.

The apparent ileal digestibility (**AID**) of starch in finely ground hybrid rye is greater than 90%, and this is also true for other cereal grains (McGhee and Stein, 2018; 2020). The apparent total tract digestibility (**ATTD**) of total dietary fiber is greater in hybrid rye (approximately 70%) than in barley, wheat, and corn, which is an indication that the total dietary fiber in hybrid rye is highly fermentable (McGhee and Stein, 2020). Although the AID of starch in ground hybrid rye is greater than 90%, the AID of gross energy is reduced in hybrid rye compared with wheat, corn, and sorghum. Among cereal grains, the ATTD of gross energy is greatest in corn (approximately 90%), but the ATTD of gross energy in hybrid rye (85%) is not different from wheat (87%) or sorghum (86%). Ultimately, the metabolizable energy (**ME**) in hybrid rye as derived in growing pigs is 3,500 kcal/kg (dry matter basis), which is less than in corn and wheat (McGhee and Stein, 2020).

The use of carbohydrate-degrading enzymes to increase the digestibility of nutrients and gross energy in rye has been studied, but results have varied. Inclusion of microbial xylanase in diets containing rye may increase the ATTD of gross energy (Nitrayová et al., 2009), but results from other experiments indicate negligible effects of xylanase supplementation on the ATTD of gross energy in rye (Thacker et al., 1991; 1992; 2002; Nørgaard et al., 2016). In an experiment testing different sources (i.e., bacterial species) of xylanase, no evidence of arabinoxylan degradation by the exogenous xylanases or improvement in dry matter, organic matter, starch, N, or crude fat digestibility was observed (Lærke et al., 2015). In a follow-up experiment, xylanase supplementation to diets for pigs was more efficacious in degrading wheat arabinoxylan than rye arabinoxylan (Lærke et al., 2015). The rye used in the experiments conducted by Thacker et al. (1991; 1992; 2002) in Canada were undoubtedly cultivars of older population rye, but in the more recently conducted experiments by Nitrayová et al. (2009), Lærke et al. (2015), and Nørgaard et al. (2016) in Europe, authors did not specify whether the rye was of population or hybrid varieties.

Using hybrid rye, Schwarz et al. (2016) and Smit et al. (2019) investigated effects of supplementing carbohydrase enzymes to diets on growth performance and carcass quality of finishing pigs. Increased back fat thickness (Schwarz et al., 2016) and increased average daily gain (**ADG**) and gain:feed (**G:F**; Smit et al., 2019) of pigs fed the enzyme-containing diets indicate that enzyme inclusion influenced energy utilization by the pigs. Overall, more research is warranted to elucidate if exogenous carbohydrase enzymes affect the ATTD of gross energy in hybrid rye, or if the observed changes in growth performance are due to other mechanisms.

Growth performance of pigs fed hybrid rye

The risk of ergot contamination, in combination with the relatively high concentration of soluble arabinoxylans in rye, have resulted in conservative upper-limit recommendations for inclusion of rye in diets for pigs to prevent reductions in growth performance and feed intake. For example, the National Swine Nutrition Guide (2010) recommends pigs up to 11 kg never be fed rye, and nursery pigs 11 to 20 kg should be allowed no more than 10% of their diet to consist of ergot-free rye. Diets for growing and finishing pigs are recommended to include a maximum of 25 and 35% ergot-free rye, respectively, whereas gestating and lactating sows should be allowed no more than 20 and 10% ergot-free rye in their diets, respectively. Because these recommendations stipulate rye must be free of ergot, and because pigs tolerate other fibrous ingredients (e.g., Stein and Shurson, 2009; Casas and Stein, 2016; Feyera et al., 2017) and changes in digesta viscosity (Thacker et al., 1991), it is possible that pigs can be fed greater amounts of rye than is currently recommended without impeding growth.

Newer cultivars of hybrid rye contain fewer antinutritional factors than older population varieties (Schwarz et al., 2015; Bederska-Łojewska et al., 2017), and the risk of ergot contamination in rye can effectively be controlled through genetic improvements and proper management of the grain pre- and post-harvest (Geiger and Miedaner, 2009; Miedaner and Geiger, 2015). Moreover, nutrient composition of population and hybrid varieties of rye differs (Strang et al., 2016; McGhee and Stein, 2018), and thus growth performance of pigs fed hybrid rye needs to be considered separately from previous research conducted with old cultivars of rye.

Weanling and nursery pigs

At present, no published data exist for growth performance of weanling or nursery pigs fed hybrid rye compared with pigs fed corn, but results of recent research indicate hybrid rye may replace wheat without influencing growth performance (Chuppava et al., 2020; Ellner et al., 2020; Wilke et al., 2020). Results of research conducted with old cultivars of hybrid rye indicate that the feeding value of rye is less than that of wheat and barley, but data for growth performance from several of these experiments were not obtained from pigs raised in group environments or under commercial conditions, and scarce information is published for newly weaned pigs. Bedford et al. (1992) conducted experiments in which either rye-based or barley-based diets were fed to 26-d old pigs housed in pairs. In the first experiment, pigs fed rye gained 4.2 kg during the 10 d experimental period, and they consumed approximately 6.9 kg of feed. In the second experiment, pigs fed barley gained 5.2 kg during the 10 d experimental period and consumed approximately 9.1 kg of feed. These values were obtained from separate experiments with pigs of different initial body weights (approximately 10 and 12 kg, respectively), and therefore cannot be directly compared; however, the general trend of reduced feed intake for rye-fed pigs has been observed in experiments conducted with older pigs as well.

Thacker et al. (1999) observed a reduction in ADG and ADFI when 17-kg pigs were fed diets containing 60% rye compared with diets containing barley, but no difference in feed efficiency was detected. Pigs were housed in groups of 4, but fed individually twice daily for 30 min per feeding. This method of feeding may have contributed to or exacerbated the observed differences in ADFI, and subsequently ADG, between pigs fed rye or barley. Pigs may consume rye more slowly or at reduced amounts compared with other feed ingredients due to the physicochemical properties of dietary fiber in rye increasing the satiety of the animal, which has also been demonstrated in humans (Isaksson et al., 2009). Solubilization of arabinoxylans increases the viscosity of intestinal fluids (Bartelt et al., 2002; Bach Knudsen et al., 2005; Le Gall et al., 2009; Le Gall et al., 2010), which may slow digesta passage rate and prolong satiety. However, selection for low- or high-viscosity rye varieties do not significantly impact growth performance of pigs, so viscosity per se is not likely to be the sole driver of voluntary feed intake of rye diets (Thacker et al., 1999).

Święch et al. (2012) reported a reduction in ADG and G:F when individually housed 20-kg pigs were fed diets in which 27% rye was included at the expense of wheat during an initial 14-d period of feeding. No differences were observed between the wheat and rye-fed groups during the second 14-d period of the experiment, which was initiated when pigs weighed approximately 30 kg. In both periods, pigs were limit fed to 5% of the individual pigs' body weight, which corresponded to approximately 90% of estimated *ad libitum* intake. Wheat has a greater concentration of ME than rye (3,908 and 3,569 kcal/kg, respectively; NRC, 2012), which likely explains the reduced ADG and G:F observed in period 1 of the experiment. The similar growth performance observed when rye replaced wheat in the second feeding period may have been due to the older pigs' more mature gastrointestinal tracts tolerating the dietary fiber component of rye better than in the initial feeding period, but the limitations of the pigs being individually housed and limit fed makes it difficult to draw general conclusions about growth performance of pigs from the experiment.

Recent data from western Canada indicate that feeding 0, 10, or 20% hybrid rye at the expense of wheat to 12 kg pigs reared in a commercial environment did not affect ADG (Bussières, 2019). The same was true when pigs were fed 0, 20, or 40% hybrid rye at the expense of wheat during the subsequent phase of the experiment. Based on the limited data available for feeding hybrid rye to pigs, it is worth considering if the conservative recommendations from the past for maximum rye inclusion rates in diets for young pigs need to be reconsidered. Research is warranted to determine how weanling and nursery pigs perform when hybrid rye replaces cereal grains other than wheat in swine diets.

Growing and finishing pigs

More research has been conducted to determine effects of feeding hybrid rye to growing and finishing pigs than has been conducted with weanling and nursery pigs, which may be due to the notion that older pigs have greater tolerance for more fibrous, less digestible feed ingredients. In several studies comparing older cultivars of rye with barley, mixed results were obtained for growth rate and feed intake of growing-finishing pigs (Thacker et al., 1991; 1992; 2002). In one experiment, pigs fed rye in a meal diet exhibited reduced ADG and ADFI compared with pigs fed a meal diet containing barley, yet no differences were observed between cereal grain types when diets were fed in pelleted form in a follow-up experiment (Thacker et al., 1991). The reduced growth rate observed when meal diets were fed was likely a result of reduced feed intake, as feed efficiency was not affected by cereal grain. With pelleted diets, however, an improvement in feed efficiency when pigs were fed rye compared with barley was observed (Thacker et al., 1991). In a similar experiment, no differences in ADG or feed efficiency were observed when pigs were fed diets containing rye or barley, however, ADFI was reduced in the pigs fed rye (Thacker et al., 1992). The same trend for ADFI was also observed when growing-finishing pigs were fed diets containing barley, low-viscosity rye, or high-viscosity rye, where pigs consumed more if fed barley than if fed either source of rye (Thacker et al., 2002). Feed efficiency was not different among treatments, but ADG was reduced for both diets containing rye compared with the diet containing barley. It appears that feed intake was a large driver of growth rate when pigs fed barley or rye were compared in the aforementioned papers (Thacker et al., 1991; 1992; 2002).

In an experiment conducted on a commercial farm in Poland, pigs were fed either a control diet consisting mainly of barley, wheat, and soybean meal or a test diet in which hybrid rye was added to the diet at the expense of barley (Schwarz et al., 2015). Experimental diets within each of the 3 dietary phases contained 10, 25, or 50% hybrid rye, respectively. During the first 2 phases of feeding (60 d in total), no differences were observed for body weights or ADG. Final body weights, however, differed between treatments after 110 d of feeding. Pigs fed the control diet weighed an average of 103 kg and pigs fed the experimental diet weighed 108 kg. Average daily gain was greater for the hybrid rye treatment than for the control treatment in the finishing phase and for the overall growing-finishing period. The increased ADG for the hybrid rye treatment also corresponded with greater ADFI during the second and third phases and for the overall experiment. Feed efficiency was not affected by treatment during phase 1, phase 3, or overall, but in phase 2, the barley-fed pigs had improved feed efficiency compared with the hybrid rye-fed pigs.

Results of a second experiment demonstrated that replacing barley with hybrid rye in liquid, pre-fermented diets also did not reduce ADFI (Schwarz et al., 2016). Average body weights did not differ during the experiment. Average daily gain was greater during the finisher phase for rye-fed pigs but did not differ in the grower phase or for the overall experiment. Overall, growing-finishing pigs fed hybrid rye in their diets performed equally or better than pigs fed the barley control diets, and unlike the older research conducted with conventional cultivars of rye, no reduction in ADFI was observed for pigs fed hybrid rye in the experiments by Schwarz et al. (2015; 2016). It is, therefore, reasonable to hypothesize that the physical, chemical, and/or nutritive composition of hybrid rye differ enough from conventional rye to elicit different feeding behaviors and growth response in growing and finishing pigs.

In a larger-scale experiment conducted in Canada, pigs tolerated hybrid rye in diets at inclusion rates as great as 20 and 50% in early growing and late finishing phases, respectively (Bussières, 2018). Control diets were based primarily on corn, wheat, barley, and soybean meal, and diets within phases were formulated to be isocaloric and to have equal concentrations of standardized ileal digestible Lys. Concentrations of hybrid rye in the *moderate* dietary treatment were 10, 15, 20, 25, and 25% in each of the 5 phases, respectively. In the *high* dietary treatment, concentrations of hybrid rye were 20, 30, 40, 50, and 50% in each phase respectively, but the individual quantities of barley, wheat, or corn that were replaced in diets with hybrid rye were not specified. There were no differences in ADG, ADFI, G:F, or mortality rate among treatments overall, but in the final phase, ADG was reduced with increased hybrid rye inclusion due to high ergot contamination in that batch of feed (unpublished data). Nonetheless, results of the experiment supports the hypothesis that hybrid rye can effectively replace portions of other cereal grains in diets for growing-finishing pigs, but concentrations of ergot alkaloids in raw ingredients and mixed diets must be taken into consideration.

Another experiment conducted under commercial farm conditions in Canada aimed to evaluate effects of exclusively replacing wheat with hybrid rye (Smit et al., 2019). Growing pigs (approximately 44 kg) were allotted to 6 dietary treatments – a low, medium, and high hybrid rye treatment, each tested without and with inclusion of exogenous xylanase. Pigs were fed in 4 phases, and other than hybrid rye, diets included wheat, wheat distiller's dried grains with solubles, and field peas. Concentrations of hybrid rye in the low hybrid rye diets were approximately 16, 21, 22, and 23% in each of the 4 feeding phases. Concentrations of hybrid rye in the medium hybrid rye diets were approximately 31, 41, 44, and 46% in each phase, respectively, and in the high hybrid rye diets, 45, 59, 64, and 66% hybrid rye was included in diets in each phase, respectively. Within each phase, canola oil was added in increasing amounts to the medium and high levels of hybrid rye diets to compensate for the lower energetic value of hybrid rye compared with wheat. No differences for average body weights were observed during the experiment for the fixed effect of hybrid rye inclusion rate, nor were there differences among hybrid rye levels for G:F. No differences were observed in the grower phases for ADFI, but overall ADFI was reduced as hybrid rye inclusion in the diet increased, and this trend was most pronounced during the finishing phases. In the first grower phase, ADG was greater in the medium and high hybrid rye treatment groups than in the low hybrid rye treatment group, but ADG was not different among treatments during the second grower phase (0.994, 0.996, 0.995 kg/d for the low, medium, and high rye treatments, respectively). In both finisher phases, ADG declined with increasing hybrid rye inclusion rate, and this trend was reflected in the ADG for the overall experiment. The positive effect on ADG that was elicited during the initial growing phase may have occurred because pigs maintained high levels of feed intake (no differences across rye levels) during that phase. In contrast, as feed intake began to drop off for the greater inclusion levels of hybrid rye during the finishing phases, ADG also declined.

Many feed ingredients with lower ME will cause pigs to consume more total feed by weight in an effort to compensate for the reduced energetic density of the feed (Baird et al., 1975; Patience, 2012). However, dietary fiber may increase gut fill and water binding capacity in the gastrointestinal tract, limiting the ability to consume enough feed to compensate for reduced ME, especially in young pigs (Avelar et al., 2011; Ndou et al., 2013; De Jong et al., 2014).

Reductions in ADFI observed in late finishing phases with increased inclusion of hybrid rye at the expense of wheat (Smit et al., 2019) may also be due to a bulking effect of hybrid rye, but the dietary fiber and non-starch polysaccharide concentrations in hybrid rye are typically only 3 to 4% greater than in wheat (McGhee and Stein, 2018; Smit et al. 2019; McGhee and Stein, 2020). It is possible that other factors like palatability and intestinal viscosity influence the feeding behavior of pigs as well.

A long-standing belief exists that rye is less palatable than other feed ingredients (e.g., Brooks, 1911; Halpin et al., 1936; Sharma et al., 1981), but in a series of two-way choice preference tests comparing individual test ingredients against a reference diet primarily based on white broken rice and soybean meal, preference values (%) for rye were numerically greater than for wheat at 30, 60, and 100% inclusion rates (Solà-Oriol et al., 2009). The experiment measured preferences of pigs naïve to all test ingredients, and preferences for rye did not differ significantly from barley, corn, or wheat and were generally greater than for oats (Solà-Oriol et al., 2009), indicating that an aversion toward the taste or smell of rye is not likely to be inherent to all pigs.

The physical behavior of hybrid rye in the gastrointestinal tract of pigs may play a role in dictating the frequency and quantity of feed consumption. Soluble arabinoxylans in rye increase digesta viscosity more than cereal grains containing less soluble fiber (Thacker et al., 1999; Bartelt et al., 2002; Bach Knudsen et al., 2005; Le Gall et al., 2009; Le Gall et al., 2010). Soluble fiber has been utilized as a mechanism to control appetite and prolong satiety in humans (Kristensen and Jensen, 2011), and a negative correlation between ileal digesta viscosity and feed preference of cereal grains by pigs exists (Solà-Oriol et al., 2007). Digestibility of nutrients, including amino acids and lipid, is also less in rye than in other cereal grains, thus more undigested protein and lipid reach the ileum (Bach Knudsen et al., 2005; McGhee and Stein, 2018). High-fat diets and excess protein upregulate hormone signaling, particularly peptide YY, from the gastrointestinal tract to the brain and have downstream effects of slowing gastric emptying and reducing appetite in humans (De Silva and Bloom, 2012). It is, therefore, possible these factors may also influence feed intake of pigs fed diets containing hybrid rye compared with other more digestible cereal grains.

Hybrid rye can successfully replace large portions of barley and wheat in diets for growing and finishing pigs without impeding growth performance, but maximizing feed intake at high inclusion rates of hybrid rye may be a challenge. A gap in knowledge exists for effects of substituting corn with hybrid rye in diets for growing-finishing pigs and thus warrants investigation.

Carcass characteristics

No differences in slaughter weight, carcass weight, dressing percent, or lean yield were observed when conventional rye substituted barley in meal diets (Thacker et al., 1991). However, when diets were fed in pelleted form, carcass weight and dressing percent were reduced for pigs fed rye compared with pigs fed barley, although authors did not provide speculation or explanation for these observations (Thacker et al., 1991). As lean yield was not influenced by cereal grain type, it is possible that changes in digestive organ weights may account for some of the difference in carcass weight and dressing percent between rye- or barley-fed pigs. Thacker et al. (2002) also observed reduced carcass weight for rye-fed pigs compared with barley-fed pigs. However, dressing percent and lean yield were not influenced by cereal grain type, so the reduced carcass weight was likely due to numerically lower live weights for rye-fed pigs compared with barley-fed pigs (102.6, 103.5, and 106.4 kg for low-viscosity rye, high-viscosity rye, and barley, respectively).

Carcass characteristics were more favorable for pigs fed diets containing hybrid rye compared with a barley control diet (Schwarz et al., 2015). Improved growth performance indicators (greater final body weight, ADG, and ADFI) corresponded to greater carcass weight, slaughter value (dressing percent), and carcass price for pigs fed hybrid rye, and hybrid rye-fed pigs had numerically greater backfat thickness and loin depth as well (Schwarz et al., 2015). However, results from an experiment conducted with pre-fermented liquid diets indicate poorer carcass characteristics in pigs fed hybrid rye, despite numerical improvements in ADG and G:F (Schwarz et al., 2016). Slaughter value (%) was reduced for the hybrid rye group, and although diets were formulated to be isocaloric and isonitrogenous, hybrid rye-fed pigs were less lean and had greater adiposity than the barley-fed control group. Bussières (2018), however, observed the opposite effect when hybrid rye substituted barley in diets for growing-finishing pigs. Pigs fed diets containing hybrid rye tended to have reduced backfat (no rye = 17.0 mm, medium rye = 16.6 mm, and high rye = 16.3 mm), but carcass yield and lean yield were unaffected by hybrid rye inclusion rate. The trend toward reduced backfat thickness with hybrid rye inclusion rate corresponds with a numeric reduction in ADG that was also observed as the inclusion of hybrid rye in the diet increased, and it is likely the control group's faster growth rate allowed more time for adipose tissue deposition prior to slaughter. The disparity in the results for backfat thickness observed by Schwarz et al. (2016) and Bussières (2018) may also be partially attributed to differences in diet formulation strategies. Results by Schwarz et al. (2016) indicated more adipose tissue deposition and less lean growth in pigs fed hybrid rye, so it is possible the experimental diets containing hybrid rye limited lean accretion and favored more fat deposition due to a reduced protein to energy ratio. Bussières (2018), on the other hand, observed less adipose tissue deposition in pigs fed hybrid rye, but no difference in lean percent, suggesting the diets provided a more adequate amount of digestible amino acids to support sustained lean muscle accretion during the experiment.

Smit et al. (2019), despite observing a tendency for reduced carcass weight with the medium and high rye treatment groups, reported no differences in dressing percent, backfat depth, loin depth, or lean yield among pigs fed different levels of hybrid rye. Regardless of hybrid rye inclusion rate, no difference in carcass revenue was observed, and the income revenue minus feed cost did not differ when hybrid rye replaced wheat, either. The results from Smit et al. (2019) indicate that replacing wheat with hybrid rye in diets for commercial pigs in western Canada will not impede profitability, and this observation is also true for replacing barley with hybrid rye according to the financial analyses by Schwarz et al. (2015; 2016) in the Polish swine industry.

Performance of sows fed hybrid rye

Substitution of hybrid rye for barley and wheat has been evaluated in diets for gestating and lactating sows (Sørensen and Krogsdahl, 2017). Reproductive performance was generally unchanged when 60% hybrid rye was included in gestation diets for sows as there were no differences in total, live, or still born pigs per litter, farrowing rate (i.e., rate of sows bred that farrowed), or need for intervention during farrowing or lactation (i.e., treatment for mastitis, metritis, or agalactia). Litter weaning weight and total litter weight gain were also not affected by inclusion of 35% hybrid rye in lactation diets, indicating that the sows' milk production and litter performance was not hindered by use of the ingredient. More research is needed to compare the impact of feeding hybrid rye with other cereal grains, particularly corn. Hybrid rye contains more insoluble, soluble, and total dietary fiber than wheat and corn, and the constituents of the fiber in hybrid rye (particularly fructooligosaccharides, arabinoxylans, mixed-linked ß-glucans, and a small amount of resistant starch), make it more fermentable than barley, wheat, corn, and sorghum (McGhee and Stein, 2018; 2020). Thus, hybrid rye is a unique ingredient for sow diets.

Sows have a high capacity to ferment fiber (Jørgensen et al., 2007) and investigating the effects of feeding different levels and compositions of dietary fiber on the growth, reproductive performance, and behavior of sows is currently a highly relevant topic of research (e.g., Sapkota et al., 2016; Feyera et al., 2017; Shang et al., 2019; Zhuo et al., 2020). In gestation, fibrous ingredients may prolong satiety, prevent frustration, and maintain a higher level of welfare, and for that reason, legislation by the European Union requires a minimum level of dietary fiber in diets for gestating and dry sows (Council of European Union, 2001), although no such legislation exists in North America. Sows are typically limit-fed during gestation to prevent problems associated with over-conditioning, but during lactation, sows are allowed *ad libitum* access to feed to maintain high levels of milk yield while preventing excess mobilization of body stores (Quesnel et al., 2008; Guillemet et al., 2012; Loisel et al., 2013). Providing less energy-dense diets that are physically more bulky to the sow during gestation may also help to prepare sows for full levels of feed during lactation (Matte et al., 1994; Farmer et al., 1996; Quesnel et al., 2008; Loisel et al., 2013). Common ingredients added to gestation diets to add dietary fiber and physical bulk include by-products such as soybean hulls, oat hulls, sugar beet pulp, wheat middlings, and wheat bran (Matte et al., 1994; Oliviero et al., 2009; Guillemet et al., 2012; Shang et al., 2019). It is possible that substituting hybrid rye for a less fibrous cereal grain may have impacts similar to adding fibrous by-products to diets.

Increased dietary fiber can alter the behavior of sows by increasing satiety and reducing general activity and stereotypic behaviors (Robert et al., 1993; 1997; Brouns and Edwards, 1994; van der Peet-Schwering et al., 2003; de Leeuw et al., 2004; Oelke et al., 2018), but results of published research do not always confirm this hypothesis (Holt et al., 2006; Sapkota et al., 2016). Sapkota et al. (2016) observed differences among dietary fiber types for stereotypic behavior in gestation, including chewing, fighting, and biting, but the effect of diet seemed to only matter within the first hour of mixing sows in new pens. Sows fed a diet containing 10.8% purified resistant starch were less likely to fight and bite other sows compared with sows fed a diet without resistant starch. This may have been a result of prolonged release of glucose and increased release of non-esterified fatty acids into the blood, thereby increasing satiety (Sapkota et al., 2016). Sows fed a highly fermentable fibrous diet had more stable glucose concentrations in the blood with fewer drops in glucose below basal level, delayed glucose spikes after feeding, and lower peak levels of insulin in the blood after a meal compared with sows fed a diet with a low concentration of fermentable fiber (de Leeuw et al., 2004). The observations of more stable glucose levels and insulin response in sows fed high-fiber diets also corresponded with fewer postural changes over time. The diet compositions differed greatly between treatments, but the largest difference between dietary treatments was the inclusion of 45% dehydrated sugar beet pulp in the fermentable high-fiber diet. Some of the observed trends were primarily due to the reduced starch concentration in the diet, but it is also possible increased production of short-chain fatty acids in the hindgut of sows stabilizes blood glucose and insulin levels several hours after feeding (de Leeuw et al., 2004; den Besten et al., 2013; Ørgaard et al., 2019; Liu et al., 2020). Serena et al. (2009) observed more stable diurnal glucose and insulin in sows fed high-fiber diets, which was a result of less starch in the diet, delayed gastric emptying slowing starch digestibility and glucose absorption, and more prolonged energy-derivatization due to hindgut fermentation of complex carbohydrates. Sugar beet pulp contains much more dietary fiber than hybrid rye (Nguyen et al., 2019; McGhee and Stein, 2020), but because hybrid rye is more fermentable than other cereal grains, perhaps similar, albeit less pronounced, effects may be elicited by replacing corn with hybrid rye in diets for sows.

Modifying sow behavior in gestation to reduce aggression and physical activity is an important objective for farmers who house sows in groups, but most farms (over 75% as of 2012; USDA, 2015) in the United States still utilize gestation stalls, and therefore, the practical and economic impact of aggressive behavior in sows is less consequential. However, feeding high levels of dietary fiber in gestation can influence lactation output and litter performance as well, which is advantageous to all producers, regardless of the type of housing system used. Quesnel et al. (2008) fed either a low-fiber diet (17.2% neutral detergent fiber) consisting primarily of barley, wheat, and soybean meal, or a high-fiber diet (30.7% neutral detergent fiber) that also contained sugar beet pulp, sunflower meal, wheat bran, soybean hulls, and corn gluten feed. In this experiment, sow performance in lactation improved when the high-fiber diet was consumed during gestation because of increased feed intake during lactation and subsequent faster litter weight gain. Increased total born piglets and greater ADFI in lactation was also observed in sows fed diets containing cellulose or guar gum in lactation compared with sows fed diets without these fiber sources, which may have been a result of changes in immunity and the intestinal microbiome (Zhuo et al., 2019).

Feeding a high-fiber diet containing barley, oats, sugar beet pulp, wheat bran, and wheat feed flour in late gestation and early lactation resulted in greater litter weight gain compared with feeding a low-fiber diet (Oliviero et al., 2009). Pig mortality was also reduced if sows were fed diets containing 23.4% total dietary fiber in late gestation and early lactation compared with 13.3% total dietary fiber, although no difference in litter weight gain was detected (Loisel et al., 2013). Addition of soybean hulls, dehulled sunflower seed, and sugar beet pellets to diets from day 102 of gestation until day 5 of lactation resulted in reductions in the number of stillborn pigs, total born pig mortality rate, proportion of piglet deaths due to low vitality, and piglet diarrhea (Feyera et al., 2017). Feeding increased fiber during gestation results in greater numbers of live born pigs per litter, and moreover, the positive effects elicited by feeding greater amounts of fiber are more pronounced when fed over multiple reproductive cycles (Reese et al., 2008). It may also be important to commence high-fiber feeding prior to insemination to maximize total litter size (Reese et al., 2008).

The types of fibers in different ingredients, in addition to the solubility, bulking characteristics, and fermentability, likely work in conjunction to dictate the extent of production effects that are observed in sow and piglet performance. Nevertheless, the improved milk yield, increased litter weight gain, and the reduced piglet mortality for sows fed diets with increased fiber are relevant when considering replacing a lower fiber cereal with hybrid rye in gestation or lactation diets.

Possible immunomodulatory and prebiotic effects of rye

Several of the dietary fibers in rye, including arabinoxylans, fructans, and mixed-linked β-glucans, have prebiotic effects (Bach Knudsen and Lærke, 2010; Gibson et al., 2010; Mendis et al., 2016; Cheng et al., 2020). Prebiotics are defined as “selectively fermented ingredients that allow specific changes, both in the composition and/or activity in the gastrointestinal microbiota that confers benefits upon host well-being and health” (Gibson et al., 2010). Dietary fiber, by definition, cannot be digested by mammalian enzymes (FDA, 2016); however, microbial populations throughout the gastrointestinal tract have varying ability to ferment fiber. Microbial colonization of the stomach is limited [100 colony-forming units (**CFU**)/mL] due to its acidic environment, but colonization of the small intestine is more substantial (10^4 to 10^8 CFU/mL; Delgado et al., 2010). The hindgut, including the cecum and colon, is colonized in the greatest amount (up to 10^{12} CFU/mL) and with the greatest diversity compared with the rest of the gastrointestinal tract (Delgado et al., 2010). The cecum and proximal colon of mammals are dominated by carbohydrate-degrading bacteria that ferment sugars and starch that escape enzymatic digestion in the small intestine as well as fermentable dietary fiber (Bach Knudsen et al., 1991; Hamer et al., 2008). The distal colon, however, is often inhabited by more proteolytic bacteria as fermentable carbohydrate substrate availability is limited (Bach Knudsen et al., 1991; Hamer et al., 2008).

Byproducts of microbial fermentation include organic acids (lactic acid and short-chain fatty acids), gases (H_2, CH_4, and CO_2), and ammonia (Bach Knudsen et al., 1991; Jensen and Jørgensen, 1994), and the rates and proportions in which byproducts of fermentation are produced depend upon the substrate that is fermented (Fredstrom et al., 1994; Burbach et al., 2017). Carbohydrate fermenting bacteria produce three main short-chain fatty acids: acetate, propionate, and butyrate, and these fatty acids can be absorbed by the large intestine epithelium and metabolized by the host for energy (Argenzio and Southworth, 1975; Bach Knudsen and Hansen, 1991; Bach Knudsen et al., 1991). Greater production of short-chain fatty acids decreases intestinal luminal pH, and mildly acidic conditions can favor the growth and proliferation of beneficial bacteria (Glitsø et al 1998; Ilhan et al., 2017), inhibit pathogenic colonization (Bouhnik et al., 2017), and reduce formation of carcinogenic bile acid degradation products (Reddy et al., 1992; Bouhnik et al., 2007; Bach Knudsen and Laerke, 2010). Unfermentable carbohydrates, which do not provide energy to the host, may benefit the host by supplying physical bulk to digesta as it moves through the gastrointestinal tract and speeding digesta transit time in the colon (Gråsten et al., 2000). The faster transit of digesta, in combination with a dilution effect from the physical bulk, reduce the opportunity for contact between pathogens or toxins with distal colonocytes (Gråsten et al., 2000).

Arabinoxylans comprise the largest proportion of dietary fiber in rye but can be fermented by only a limited number of bacterial species, including *Bacteroides ovatus, Roseburia intestinalis,* and relatives of *Ruminococcus flavefaciens* (Bach Knudsen and Laerke, 2010). However, fermentation of arabinoxylans increases lactobacilli and bifidobacteria, two of the beneficial bacteria of the mammalian gastrointestinal tract (Hughes et al., 2007; Pessione, 2012; Yang et al., 2013). Increases in lactobacilli and bifidobacteria following arabinoxylan consumption are the result of cross-feeding degradation products of other bacteria species equipped to degrade complex arabinoxylan polymers (Bach Knudsen and Laerke, 2010; Rivière et al., 2014). Arabinoxylans are present in the endosperm, aleurone, and pericarp/testa of the rye grain, and the fermentability of arabinoxylans derived from each of these areas differ (Bach Knudsen and Hansen, 1991; Glitsø et al., 1998; 1999; Bach Knudsen and Lærke, 2010). Endosperm arabinoxylans are highly soluble and are fermented quickly in the cecum and proximal colon, whereas the aleurone arabinoxylan are fermented more slowly and more distally in the colon (Le Gall et al., 2009), which is beneficial for suppressing proteolytic fermentation.

Dietary fiber, including arabinoxylans, may directly impact the inflammatory response in the gut. Cao et al. (2011) investigated the effects of oral supplementation of wheat arabinoxylan to rats with transgenic tumors and discovered anticarcinogenic effects via stimulation of the immune system. Some of the indices of immune stimulation and tumor suppression, including serum interleukin-2 concentration, natural killer cell activity, macrophage phagocytotic activity, and overall tumor necrosis were stimulated by wheat bran arabinoxylan treatment. Wheat bran arabinoxylan was associated with activation of T- and B-lymphocytes and enhanced humoral and cell-mediated immunity (Cao et al., 2011), thus it is possible consumption of rye arabinoxylan may modulate the immune system and confer anticarcinogenic effects as well.

Inulin-type fructans are some of the most widely-studied prebiotic dietary fibers in the human health sector, although purified fructans derived from chicory root and Jerusalem artichoke are the most frequently studied sources of fructan (Van den Ende et al., 2002; Mendis and Simsek, 2014; Franco-Robles and López, 2015). Chicory root, Jerusalem artichoke, and garlic contain 7 to 9% fructans (Jovanovic-Malinovska et al., 2014), whereas the concentration of fructans in hybrid rye is approximately 4 to 7% (Karpinnen et al., 2003; Laatikainen et al., 2016; McGhee and Stein, 2020). Nevertheless, it is possible the results of feeding purified fructan or fructans derived from other ingredients can be extrapolated to what may occur when hybrid rye fructan is consumed by pigs. Like arabinoxylans, which seem to have direct interactions with immune system components (Cao et al., 2011), fructans have direct immune cell-modulating capabilities (Peshev and Van den Ende, 2014). As a prebiotic, fructan consumption results in shifts of intestinal microbe populations, including increased bifidobacteria (Bouhnik et al., 2007; Schokker et al., 2018). One of the most important outcomes of fructan and arabinoxylan consumption, though, is increased production of butyrate (Bach Knudsen et al., 1991; Bach Knudsen et al., 2005; Bach Knudsen and Lærke, 2010). Butyrate is the preferred energy substrate for colonic epithelial cells (Roediger, 1980) and supports maintenance and function of individual colonocytes. Butyrate also improves intestinal mucosa health and barrier function in the colon (Hamer et al., 2008; Vogt et al., 2014), has direct effects on gene expression via its inhibitory effect on histone deacetylase (Chang et al., 2014), and may improve redox status and reduce oxidative stress by modulating antioxidant enzymes (glutathione-S-transferase; Ebert et al., 2003). Decreased inflammation in humans with gut diseases has been demonstrated via butyrate inhibition of NF- κB, a transcription factor involved in the control of pro-inflammatory gene expression (Hamer et al., 2008), and through the activation of PPARγ, which confers anti-inflammatory effects in the colon (Hamer et al., 2008; Nepelska et al., 2017). Butyrate also contributes to feelings of satiety because it can stimulate L-cells in the colon to secrete glucagon-like peptide 1 (GLP-1) and peptide YY (Hamer et al., 2008; Tolhurst et al., 2012).

Feeding rye to pigs promotes beneficial shifts in intestinal bacterial populations and increases butyrate production (Bach Knudsen et al., 2005; Burbach et al, 2017). Although characterizing effects of dietary fiber is complex, and not all mechanisms are fully elucidated, the intestinal luminal environment and its microbial inhabitants are highly intertwined with the innate and adaptive immune system of the host (Delgado et al., 2010). Modulation of the immune system via feeding prebiotic dietary fiber may be beneficial to minimize the energetic cost of supporting the immune system (i.e., reduce inflammation), ameliorating overall health status, and ultimately improving production parameters. For example, diarrhea in young pigs after weaning may be prevented or reduced with fructan supplementation (Oli et al., 1998), and in finishing pigs, fructan supplementation improves growth performance while reducing fecal *E. coli* concentrations and fecal excretion of noxious fermentation products (Zhao et al., 2013). More research is needed to investigate the possible health-promoting effects of feeding hybrid rye to different age groups of pigs.

Conclusions

Nutrient composition and digestibility of energy and nutrients in hybrid rye differs from older cultivars of conventional rye and from other cereal grains, but the ingredient is likely a suitable alternative to wheat or barley in diets for pigs. Limited research has been conducted to investigate effects of feeding hybrid rye to pigs, and to our knowledge, no published data exist for growth performance of nursery pigs fed hybrid rye. Replacing wheat or barley with hybrid rye in diets for growing-finishing pigs results in few differences in growth performance, although feed intake may be reduced when hybrid rye is fed at high inclusion rates. Hybrid rye contains standardized ileal digestible amino acids and standardized total tract digestible P that are not different from corn, but the ME in hybrid rye is less than in corn. Effects of substituting corn for hybrid rye in diets for pigs have not been reported and should be investigated. It is also possible the unique fiber composition in hybrid rye, which includes relatively high amounts of fermentable arabinoxylans and fructans compared with other cereal grains, may alter the health status or performance of pigs, but research to confirm this hypothesis is needed.

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CHAPTER 3: Hybrid rye may replace up to 75% of the corn in diets for gestating and lactating sows without negatively impacting sow and piglet performance

Abstract

An experiment was conducted to test the hypothesis that hybrid rye can replace up to 75% of the corn in gestation and lactation diets without negatively affecting sow and litter performance. For gestation and lactation, a corn-soybean meal control diet and 3 diets in which hybrid rye replaced 25, 50, or 75% of corn were formulated. Fifty replicate sows per treatment were randomly allotted by parity to 4 treatments. Sow body weights were recorded on day 7 and day 105 of gestation, within 24 h after farrowing, and on the day of weaning (19.51 ± 1.08 d post-partum). Number and weights of pigs were determined within 24 h of farrowing, and blood samples were obtained from sows on day 105 of gestation, day 13 of lactation, and from pigs at weaning. Milk samples were collected on day 13 of lactation. Pig mortality data were analyzed using SAS Proc Glimmix with binomial distribution, whereas all other data were analyzed using Proc Mixed. Statistical models included the fixed effects of diet and parity and the random effect of group. Diet did not influence sow body weight or sow average daily gain (ADG) at any point in the experiment. Diet did not affect number or weights of total, live, or still born pigs, but there was an increase and then a reduction in the number of pigs weaned, litter wean weight, and litter ADG as hybrid rye inclusion in the diets increased (quadratic, $P < 0.05$). Pig mortality, as well as the proportion of pigs crushed by sows, 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 nor in pigs on the day of weaning, but interleukin (IL)-4, IL-10, and IL-18 on day 13 of lactation increased (quadratic, $P < 0.05$) as hybrid rye inclusion increased in diets. Likewise, IL-1α, IL-1 receptor antagonist, IL-6, and tumor necrosis factor-α tended (linear $P < 0.10$) to decrease as hybrid rye in diets increased. Milk urea N increased (linear, $P < 0.05$) with increased hybrid rye in the diet, but no other differences in milk composition were observed among treatments. In conclusion, replacing corn with hybrid rye in gestation and lactation diets had no effect on sow body weight changes nor on number or birthweights of pigs. Overall, diets in which 25% or 50% of corn was replaced with hybrid rye resulted in improved sow lactation performance, and replacing 75% of corn with hybrid rye resulted in sow and litter performance traits not different from that of sows fed the corn-based control treatment.

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

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

Introduction

Rye is used in the human food industry for baking and distilling, as a substrate for biogas production, and as a livestock feed (Bengsston et al., 1992; Bach Knudsen, 1997; Hübner et al., 2011; Balcerek et al., 2016). As a livestock feed, 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 anti-nutritional factors, including alkylresorcinols, trypsin inhibitors, and non-starch polysaccharides. However, newer varieties of hybrid rye contain fewer anti-nutritional 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 diets containing a portion of hybrid rye during gestation and lactation performed as well as sows fed control diets consisting of 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 with that of sows fed corn, and this is important because most sows in the United States and many other countries are fed corn-soybean meal diets. Although rye has greater concentrations of non-starch polysaccharides than corn, mature pigs have a high capacity to ferment fiber (Jørgensen et al., 2007). Thus, it was hypothesized that hybrid rye may replace some of the corn in diets for gestating and lactating sows without influencing sow body weight changes, sow lactation performance, or litter growth performance.

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.

Experimental diets

Four gestation diets and 4 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 3 additional diets in which hybrid rye replaced 25, 50, or 75% of the corn were formulated (Table 3.1). The experiment was conducted from October, 2018, to August, 2019. 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 4 treatments. Eleven to 20 sows were bred and farrowed at a time, and 11 groups of sows were used. 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 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 post-farrowing, all sows were offered 4.5 kg feed daily. From 4 d post-farrowing, and until weaning, all sows were offered feed on an *ad libitum* basis. Feed refusals were collected and measured daily from day 106 of gestation until 4 d post-farrowing and on the day of weaning. All litters were offered a standard creep feed diet at day 14 post-farrowing, 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 post-farrowing. 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 only within treatment groups. 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 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 for serum analyses 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 post-farrowing. Blood samples for serum analyses were also collected from the third heaviest barrow from each of these sows' litters at weaning. Blood was collected in serum vacutainer tubes containing spray-coated silica as a serum clot activator, allowed to clot, and 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 post-farrowing 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 4 functional teats on each side of the udder, for a total of 50 mL of milk. Milk samples were stored at −20 ºC 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), as well as for dry ash (method 942.05; AOAC Int., 2007). The gross energy in the diets and in the 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 post-column 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].

Mycotoxin analyses on the corn and hybrid rye ingredients were performed 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 were 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.

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 5 total pigs were born, or if 3 or more response variables were identified as outliers. Of the 188 sows that completed the experiment, 7 sows were excluded from statistical analyses based on these criteria (1 sow was excluded from the 25% rye treatment, and 2 sows were excluded from each of the other 3 treatments). After the removal of the 7 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 ($\alpha = 0.05$) 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 $P \leq 0.05$ and considered a trend at $0.05 < P \leq 0.10$.

Results

The analyzed composition of experimental diets and hybrid rye ingredient were within expected ranges (Table 3.2). 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 3.3). 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 dietary treatments (quadratic, $P < 0.05$).

There were no differences among dietary treatments for number of total pigs born 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 3.4). Sows fed diets in which 25 or 50% of corn was replaced with 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 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. Pre-weaning 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 ($P < 0.10$).

In general, the composition of the milk on day 13 of lactation was not influenced by diet (Table 3.5), although there was a linear increase ($P < 0.05$) in milk urea N as dietary hybrid rye inclusion increased. Milk somatic cell count tended to increase as rye inclusion increased (quadratic, $P < 0.10$). No difference was observed for IgG in milk on day 13 of lactation.

Serum IgG in sows did not differ among dietary treatments at day 105 of gestation, and the same was true for all measured cytokines and chemokines (Table 3.6). 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 exhibited no differences in the 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 3.7). 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 our knowledge, no data for effects of substituting hybrid rye for corn in diets for sows have been reported. Because sows have a high capacity to ferment fiber (Jørgensen et al., 2007), and hybrid rye contains more soluble and insoluble dietary fiber than corn (McGhee and Stein, 2018; 2020), 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, as inulin-type fructans, soluble arabinoxylans, and mixed-linked β-glucans, all present 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 attributes at birth and in sow blood characteristics in late gestation indicate 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., 2008; Guillemet et al., 2012; Loisel et al., 2013). The observation that sow body weights did not differ among treatments during the experiment supports the hypothesis that sow performance was not hindered by 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., 2008; 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 high inclusion rates. 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 estimated milk yield contributing to more robust wean groups, the higher-yielding treatment groups also tended to have reduced pre-weaning litter mortality. It was hypothesized that the satiating effects of dietary fiber 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 in the present experiment, 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. Differences in milk composition were not observed and can, therefore, be ruled out as a reason for improved litter performance, but because milk intake was not directly determined, additional research is required to determine if hybrid rye increases milk production.

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 lactating sows fed 25 or 50% hybrid rye replacement treatments. 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), and thus circulating cytokine concentrations measured from peripheral blood may partially conflate systemic versus localized and chronic versus acute inflammation in the body.

Because no differences were observed among treatments for concentrations of cytokines in late gestation, it is possible 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 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, 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 pro-inflammatory 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 the immune status of sows did not directly impact the quantified immune markers in average-weight pigs from their litters.

Conclusions

Replacing corn with hybrid rye in gestation and lactation diets had no effect on sow body weight changes nor on number or birthweights 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 pre-weaning mortality. 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 the corn-soybean control treatment. Future research should focus on determining effects of hybrid rye on butyrate synthesis, intestinal health, and milk production. Research to determine the impact of hybrid rye on sow behavior in lactation is also warranted.

Tables

Table 3.1. 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

Table 3.1 (cont.)

[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.

Table 3.2. 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 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

Table 3.2 (cont.)

	Gestation[1]				Lactation[1]				Hybrid
Item	0%	25%	50%	75%	0%	25%	50%	75%	rye
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.

Table 3.3. Performance of sows fed diets in which 0, 25%, 50%, or 75% of corn from 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
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

Table 3.3 (cont.)

	Diet[2]					*P* – values	
Item	0%	25%	50%	75%	SEM	Linear	Quadratic
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 (Cook and Cole, 2000).

Table 3.4. Performance of litters 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
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

Table 3.4 (cont.)

	Diet[2]					*P* – values	
Item	0%	25%	50%	75%	SEM	Linear	Quadratic
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 3.5. Composition of milk samples collected approximately 13 d post-farrowing 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
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.

Table 3.6. 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

Table 3.6 (cont.)

	Diet[2]					*P* – values	
Item	0%	25%	50%	75%	SEM	Linear	Quadratic
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.

Table 3.7. 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.

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CHAPTER 4: Metabolizable energy and apparent total tract digestibility of gross energy is reduced in hybrid rye compared with corn when fed to gestating sows

Abstract

The metabolizable energy (ME) in hybrid rye is less than in corn when fed to growing pigs, but because sows have greater capacity for fermenting fiber, an experiment was conducted to test the hypothesis that the ME in hybrid rye and corn will not differ when fed to gestating sows. It was also hypothesized that an exogenous enzyme blend will increase the apparent total tract digestibility (ATTD) of gross energy (GE) in hybrid rye and in corn. Thirty-six sows in mid-gestation were allotted to 4 dietary treatments. Two diets were formulated to contain approximately 97% corn or 97% hybrid rye, and 2 additional diets were formulated by adding 0.01% microbial enzyme cocktail (Superzyme, Canadian Bio-Systems Inc., Calgary, AB, Canada) to the 2 initial diets at the expense of cereal grain. An adaptation period of 5 d was followed by 4 d of total feces and urine collection according to the marker-to-marker approach. There was no interaction between cereal grain and enzyme inclusion for any tested variable, nor was there an effect of enzyme inclusion. Daily feed intake, fecal output, GE intake, GE output from feces, and GE output from urine were greater ($P < 0.05$) for sows fed hybrid rye than for sows fed corn. The digestible energy (DE) and ME in hybrid rye was less ($P < 0.05$) than in corn, and the ATTD of GE tended ($P < 0.10$) to be reduced in hybrid rye compared with corn, although the difference was only about 1%. Previous research indicates that hybrid rye has less ME and reduced ATTD of GE compared with corn when fed to growing pigs, and the same is

true for sows, although the difference may be less pronounced in sows. The exogenous enzyme blend used in the present experiment did not improve the ATTD of GE in either cereal grain.

Key words: cereal grains, corn, digestibility, energy, gestating sows, hybrid rye

Abbreviations

ATTD	apparent total tract digestibility
DE	digestible energy
DM	dry matter
GE	gross energy
ME	metabolizable energy

Introduction

When fed to growing pigs, the metabolizable energy (**ME**) in hybrid rye is less than in corn, which is likely due to the greater concentration of dietary fiber and the reduced digestibility of starch in hybrid rye compared with corn (McGhee and Stein, 2020a). However, the ME derived by a pig from a feed ingredient depends on the physiological stage of the pig, because mature pigs have greater capacity for fermenting fiber than younger pigs (Jørgensen et al., 2007; Casas and Stein, 2017). Therefore, the digestible energy (**DE**) in feed ingredients is greater when measured in sows or finishing pigs than when measured in growing pigs, which is likely due to increased digestibility of fiber and longer digestive retention time (Noblet and Shi, 1993; Goff et al., 2002; Lowell et al., 2015; Casas and Stein, 2017). In a previous experiment conducted at the University of Illinois, no differences among treatments were observed for average daily feed intake or average daily gain in gestating sows fed diets with varying concentrations of corn and hybrid rye, which indicates the DE and ME in these two ingredients may not differ when fed to sows (McGhee and Stein, 2020b). Additionally, blends of exogenous carbohydrase enzymes may increase the digestibility of energy in wheat, but it is unclear if exogenous carbohydrases also increase the digestibility of energy in hybrid rye (Nortey et al., 2008; Nitrayová et al., 2009; Lærke et al., 2015; Nørgaard et al., 2016). Therefore, the objective of this experiment was to determine the DE, ME, and apparent total tract digestibility (**ATTD**) of gross energy (**GE**) in corn and in hybrid rye when fed to gestating sows without and with inclusion of an exogenous microbial enzyme blend. It was hypothesized that the DE and ME in hybrid rye would not differ from corn when fed to sows and that the exogenous enzyme blend would increase the ATTD of GE in hybrid rye and in corn.

Materials and Methods

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

Animals, housing, and experimental design

A 2 × 2 factorial experiment was conducted to compare the ATTD of GE in corn and in hybrid rye, without and with the inclusion of an exogenous microbial enzyme blend when fed to gestating Camborough sows (Pig Improvement Company, Henderson, TN, USA). A total of 36 sows (minimum parity = 2, i.e., no pregnant gilts were used) were randomly allotted to 4 dietary treatments on day 50 of gestation. Sows were housed in individual metabolism crates equipped with a self-feeder, a nipple waterer, and slatted floors to allow for the total, but separate, collection of urine and fecal materials. Throughout the experiment, sows had *ad libitum* access to water. Sows were limit fed at 1.5 times the estimated ME requirement for maintenance (100 kcal

ME per kg body weight$^{0.75}$; NRC, 2012). The ME of each diet was estimated based on ME values for hybrid rye as determined in growing pigs (McGhee and Stein, 2020a) and for corn according to NRC (2012). Feed was provided each day in 2 equal meals at 0800 and 1700 h. Orts were collected daily prior to feeding the morning meal, pooled for the duration of the collection period, and weighed at the conclusion of the experiment. Feed consumption was recorded daily, and diets were fed for 11 d. The initial 5 d were considered the adaptation period to the diet, whereas urine and fecal material were collected during the following 4 d according to standard procedures using the marker-to-marker approach (Adeola, 2001). Urine was collected in buckets over a preservative of 50 mL of hydrochloric acid. Fecal samples and 20% of the collected urine were stored at −20 ºC immediately after collection.

Experimental diets

Two diets were formulated to contain approximately 97% corn or 97% hybrid rye. The same source of hybrid rye as used in chapter 3 was used in the present experiment. Two additional diets were formulated by adding 0.01% microbial enzyme cocktail (Superzyme, Canadian Bio-Systems Inc., Calgary, AB, Canada) to the initial 2 diets at the expense of cereal grain. All diets were formulated to meet or exceed the estimated requirements of vitamins and minerals for gestating sows (Table 4.1; NRC, 2012). According to the manufacturer, the enzyme product was formulated to contain the following minimum enzyme activities: xylanase, 8,500 units/g; glucanase, 3,000 units/g; invertase, 4,000 units/g; protease, 6,500 units/g; cellulase, 7,000 units/g; amylase, 80,000 units/g; and mannanase, 750 units/g. The enzyme cocktail contained fermentation extracts derived from *Trichoderma reesei*, *Saccharomyces cerevsiae*, *Aspergillus niger*, *Aspergillus oryzae*, *Bacillus subtilis*, *Bacillus licheniformis*, and *Rhizopus oryzae*.

Chemical analyses

At the conclusion of the experiment, urine samples were thawed and mixed within pig and diet, filtered through a Whatman grade 4 filter paper, and a sub-sample was lyophilized. Fecal samples and orts were dried in a 50 °C forced air drying oven, and fecal samples were ground using a 1-mm screen in a Wiley mill (model 4; Thomas Scientific, Swedesboro, NJ, USA). Diet samples were finely ground prior to analysis using a coffee grinder. Diet samples were analyzed by Canadian BioSystems, Inc. (Calgary, AB, Canada) to confirm expected xylanase activity. All diet and fecal samples were analyzed for dry matter (DM; method 930.15; AOAC Int., 2007) and for ash (method 942.05; AOAC Int., 2007). 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 protein was calculated as 6.25 × N. The concentration of total starch in diets was analyzed by the glucoamylase procedure (method 979.10; AOAC Int., 2007), which yields the enzymatically hydrolyzed starch in the sample. Diet samples were analyzed for total acid-hydrolyzed ether extract by acid hydrolysis using 3*N* HCl (AnkomHCl, Ankom Technology, Macedon, NY, USA) prior to fat extraction. Diets were also 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. 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]. Diet samples were analyzed for insoluble and soluble dietary fiber on an Ankom Total Dietary Fiber Analyzer (method 991.43; AOAC Int., 2007).

Total dietary fiber was considered the sum of isoluble dietary fiber and soluble dietary fiber. The GE in diets, fecal samples, and urine samples were measured using an isoperibol bomb calorimeter (model 6400, Parr Instruments, Moline, IL, USA) with benzoic acid used as the standard for calibration.

Calculations and statistical analyses

The DE and ME in diets were calculated by subtracting GE in feces and GE in feces and urine, respectively, from GE in the diet (NRC, 2012). The ATTD of GE was calculated for each diet using the following equation:

$$\mathrm{ATTD_{GE}}, \% = \left(\frac{\mathrm{GE_{intake}} - \mathrm{GE_{feces}}}{\mathrm{GE_{intake}}}\right) \times 100$$

Sow was considered the experimental unit and data were summarized for each dietary treatment. Data were analyzed using SAS 9.4 (SAS Institute Inc., Cary, NC, USA). Normality of 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 detected. Data were analyzed by the MIXED procedure as a 2 × 2 factorial design with the statistical model including the fixed effects of cereal grain and enzyme inclusion, as well as the random effect of block and replicate within block. Least square means were estimated for each treatment group using the LSMEANS statement in PROC MIXED, and when significant, means were separated using the PDIFF option in SAS. Results were considered significant at $P \leq 0.05$ and considered a trend at $0.05 < P \leq 0.10$.

Results

The analyzed composition of diets were within expected ranges (Table 4.2). There was no interaction between cereal grain and enzyme inclusion for any tested variable, nor was there an effect of enzyme inclusion (Table 4.3). Daily DM feed intake was greater ($P < 0.05$) by sows fed hybrid rye than by sows fed corn, and the same was true for daily DM fecal output ($P < 0.05$), daily GE intake ($P < 0.05$), daily GE output from feces ($P < 0.05$), and daily GE output from urine ($P < 0.05$). The DE and ME in hybrid rye were less ($P < 0.05$) than in corn, and the ATTD of GE tended ($P < 0.10$) to be reduced in hybrid rye compared with corn.

Discussion

Hybrid rye contains less starch, but more insoluble and soluble dietary fiber, than corn, and in growing pigs, the fiber from hybrid rye is more fermentable than the fiber from corn (McGhee and Stein, 2020a). The apparent ileal digestibility of starch in hybrid rye is slightly reduced compared with corn though, which helps to explain why, when determined in 28 kg pigs, the ATTD of GE in corn and hybrid rye was 89.5% and 85.1%, respectively (McGhee and Stein, 2020a). In growing pigs, the ME of hybrid rye was determined to be approximately 3,480 kcal/kg DM, whereas the ME in corn was 3,732 kcal/kg DM. Despite the reduced ME in hybrid rye, growth performance of gestating sows did not differ when corn was replaced with hybrid rye in diets in a previously conducted experiment at the University of Illinois (McGhee and Stein, 2020b). Thus, it was hypothesized that due to greater nutrient digestibility and capacity for hindgut fermentation of fiber by gestating sows compared with growing pigs, the ME in corn and hybrid rye would not differ when measured in gestating sows. The hypothesis was not supported, as hybrid rye had reduced DE, ME, and ATTD of GE compared with corn; however, the differences appeared to be less than the differences observed in growing pigs (McGhee and Stein, 2020a).

The digestibility of GE in hybrid rye fed to gestating sows has not been reported until now, but the digestibility of GE in an older cultivar of population rye was 87.0% in sows and 86.0% in growing pigs (Fernández et al., 1986). In an experiment conducted in 2015 using the direct method of nutrient digestibility determination, the ATTD of GE in corn was greater in gestating sows (88.2%) than in growing pigs (85.8%), and the ME in corn was 3,666 and 3,454 kcal/kg DM in gestating sows and growing pigs, respectively (Lowell et al., 2015). Although the values determined by Lowell et al. (2015) are less than what was observed in the present experiment, the difference in energy digestibility by growing pigs and gestating sows (212 kcal/kg DM) is notable. In the present experiment, the ME in corn and in hybrid rye, respectively, were 243 and 329 kcal/kg DM greater than previously determined in growing pigs (McGhee and Stein, 2020a), indicating that gestating sows obtained more energy from these ingredients than growing pigs. Furthermore, the ME in hybrid rye and corn differed by only 166 kcal/kg DM in the present experiment compared with the 250 kcal/kg DM difference in ME observed between the ingredients when determined in growing pigs (McGhee and Stein, 2020a). These observations support the hypothesis that dietary fiber from cereal grains is better utilized by sows than by growing pigs due to the mature gastrointestinal tract and greater capacity for hindgut fermentation in sows (Fernández et al., 1986; Noblet and Shi, 1993; Jørgensen et al., 2007).

Exogenous enzymes like xylanase are frequently included in diets for pigs to increase the energy contribution from dietary fiber, but the mechanisms of action are not entirely elucidated, and the efficacy of xylanases differ among sources as well as among ingredient substrates (Adeola and Cowieson, 2011; Petry and Patience, 2020). Inclusion of microbial xylanase in diets containing rye resulted in approximately 2% greater ATTD of GE when fed to growing pigs

(Nitrayová et al., 2009), but under different experimental conditions, the digestibility of energy was not changed by inclusion of microbial xylanase in diets containing rye (Nørgaard et al., 2016). Inclusion of exogenous carbohydrase enzymes in diets containing hybrid rye for finishing pigs resulted in increased backfat thickness (Schwarz et al., 2016) and increased average daily gain and gain:feed (Smit et al., 2019), but to our knowledge, the effects of including enzymes in hybrid rye-based diets for sows has not been reported. The ATTD of GE in diets based primarily on barley and wheat was increased by inclusion of an exogenous xylanase in diets fed to lactating sows (Zhou et al., 2018); however, no effects of enzyme inclusion were observed in the present experiment. It is possible a longer period of feeding exogenous enzymes is required to elicit a response in corn-based diets (Petry et al., 2020), which may be true for diets based on hybrid rye as well. It is also possible the enzyme mixture tested in the present experiment will be more efficacious in corn or hybrid rye-based diets fed to younger pigs compared with sows because baseline nutrient digestibility and fiber fermentation in sows is likely closer to maximum biological capacity. Further research to test the effects of different microbial enzyme mixtures in diets containing hybrid rye for growing and finishing pigs is warranted.

Conclusions

It was hypothesized that energy values would not differ between corn and hybrid rye when fed to gestating sows based on the previous observation that growth performance of sows did not differ when hybrid rye replaced corn in gestation diets. This hypothesis was not supported because DE, ME, and ATTD of GE was greater in corn than in hybrid rye. However, the results of the present experiment indicate that the difference in ME between corn and hybrid rye is less pronounced in sows compared with growing pigs, likely due to the greater capacity for carbohydrate digestion and fermentation in sows than in growing pigs.

Tables

Table 4.1. Ingredient composition of experimental diets

Item	Corn	Hybrid rye	Corn + Enzyme	Hybrid rye + Enzyme
Ingredient, %				
Cereal grain	97.50	97.65	97.30	97.45
Limestone	0.75	1.00	0.75	1.00
Dicalcium phosphate	1.20	0.80	1.20	0.80
Salt	0.40	0.40	0.40	0.40
Vitamin-mineral premix[1]	0.15	0.15	0.15	0.15
Enzyme premix[2]	-	-	0.20	0.20

[1]The vitamin-micromineral premix provided the following quantities of vitamins and microminerals per kg of complete diet: Vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 as cholecalciferol, 2,208 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride,0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper sulfate and copper chloride; Fe, 126 mg as ferrous sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese sulfate; Se, 0.3 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc sulfate.

[2]Enzyme premix consisted of 5% Superzyme enzyme (Canadian Bio-Systems Inc., Calgary, AB, Canada) and 95% cereal grain. At 0.20% inclusion, the premix was expected to contribute 850 xylanase units per kg complete feed.

Table 4.2 Analyzed composition of experimental diets

Item	Corn	Hybrid rye	Corn + Enzyme	Hybrid rye + Enzyme
Calculated ME[1], kcal/kg	3,310	3,078	3,310	3,078
Xylanase activity, units/kg	190	47	790	1,287
Gross energy, kcal/kg	3,660	3,681	3,635	3,667
Dry matter, %	83.59	85.91	83.58	86.01
Ash, %	2.86	3.01	2.80	3.00
Crude protein, %	6.86	9.73	6.58	9.27
Starch, %	58.33	50.13	58.63	50.88
Acid-hydrolyzed ether extract, %	4.43	2.57	4.16	2.35
Insoluble dietary fiber, %	10.60	14.40	9.20	13.50
Soluble dietary fiber, %	ND[2]	2.30	1.40	3.30
Total dietary fiber, %	10.60	16.70	10.60	16.80
Arg, %	0.33	0.45	0.28	0.47
His, %	0.20	0.21	0.19	0.22
Ile, %	0.26	0.35	0.25	0.34
Leu, %	0.83	0.60	0.81	0.61
Lys, %	0.24	0.37	0.21	0.38
Met, %	0.13	0.15	0.14	0.17
Cys, %	0.15	0.22	0.14	0.23
Phe, %	0.34	0.45	0.33	0.45
Thr, %	0.25	0.31	0.23	0.32
Trp, %	0.06	0.09	0.05	0.09
Val, %	0.33	0.45	0.31	0.45

Table 4.2 (cont.)

[1]ME = metabolizable energy. Metabolizable energy was calculated rather than analyzed. Calculations were based on the value 3,150 kcal/kg ME in hybrid rye (McGhee and Stein, 2020), and the value 3,395 kcal/kg ME in corn (NRC, 2012).

[2]ND = Not detected.

Table 4.3 Apparent total tract digestibility (ATTD) of gross energy (GE) and concentration of digestible energy (DE) and metabolizable energy (ME) in corn and hybrid rye, without and with microbial enzyme blend as determined in gestating sows[1]

Item	Corn	Hybrid rye	Corn + Enzyme	Hybrid rye + Enzyme	SE	*P*-value		
						Grain	Enzyme	Interaction
Feed intake, kg DM/d	2.11	2.27	2.06	2.32	0.063	0.002	0.967	0.431
Fecal output, kg DM/d	0.18	0.22	0.18	0.24	0.016	0.006	0.539	0.602
GE intake, kcal/d	9,220	9,720	8,951	9,896	272.0	0.013	0.865	0.419
GE output from feces, kcal/d	834	1,007	842	1,049	70.0	0.011	0.726	0.808
GE output from urine, kcal/d	217	287	207	237	22.9	0.026	0.172	0.361
ATTD of GE, %	90.9	89.7	90.7	89.5	0.61	0.055	0.747	0.981
DE, kcal/kg DM	4,082	3,939	4,046	3,914	27.2	<0.001	0.282	0.829
ME, kcal/kg DM	3,975	3,809	3,942	3,811	30.2	<0.001	0.612	0.550

[1]Least square means for dietary treatments represent 9 observations.

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CHAPTER 5: Nursery pigs prefer a corn-based diet to a diet containing a mixture of corn and hybrid rye when given the choice, but growth performance is not hindered if hybrid rye replaces portions of corn in diets for nursery pigs

Abstract

Two experiments were conducted to test the hypotheses that feed preference and growth performance will not differ if hybrid rye replaces portions of corn in diets for nursery pigs. In experiment 1, 40 barrows (9.2 ± 1.0 kg) were housed in 20 pens for 8 d. Each pen had 2 identical feeders containing a corn-based diet or a diet in which 50% of the corn was substituted with hybrid rye. Each day, feed allowance and disappearance were recorded, and feeder positions were switched. In experiment 2, 160 weanling pigs (6.0 ± 0.7 kg) were randomly allotted to 40 pens and 5 treatments [Phase 1 (day 1 to 7): 0, 3, 6, 9, or 12% hybrid rye; Phase 2 (day 8 to 21): 0, 5, 11, 16, or 21% hybrid rye; Phase 3 (day 22 to 34): 0, 15, 30, 45, or 60% hybrid rye]. Individual pig 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 1 pig per pen on day 21 and on day 34. Results of experiment 1 indicated preference was greater ($P < 0.05$) for the corn-based diet than for the corn-hybrid rye mixed diet on day 2, 3, 6, 8, and for the overall period. Overall, pigs preferred the corn-based diet 56.6% of the time and the corn-hybrid rye mixed diet 43.4% of the time. In experiment 2, there were no differences among treatments for body weight or average daily gain. During phase 3 and for the overall experiment, pigs fed diets with 60% 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 6 or 9% hybrid rye inclusion in phase 1, but the reduction was not observed with 12% hybrid rye inclusion. Blood urea N was elevated (day 21, quadratic, $P < 0.05$; day 34, linear, $P < 0.05$) with the greatest dietary hybrid rye inclusion. Concentration of neutrophils was reduced and then increased (quadratic; day 21, $P < 0.10$; day 34, $P < 0.05$) with greater hybrid rye inclusion in the diet, and the same was true for total white blood cells on day 34 (quadratic, $P < 0.10$). To conclude, nursery pigs preferred corn-based diets to diets containing a mix of corn and hybrid rye when given the choice. When the choice was not given, nursery pigs consumed more feed as hybrid rye was added to diets, likely as a result of hybrid rye containing less metabolizable energy compared with corn.

Key words: cereal grains, corn, feed preference, hybrid rye, nursery pigs

Abbreviations

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

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 of corn (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 the production of butyrate, reducing the pH in the large intestine, and supporting the proliferation of beneficial bacteria in the gut (May et al., 1994; Karppinen et al., 2003; Le Gall et al., 2009; Bach Knudsen et al., 2005; 2016; 2017; Zhao et al., 2013). Conversely, 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 in 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 hybrid rye (Chuppava et al., 2020; Ellner et al., 2020; Wilke et al., 2020). To our knowledge, no data have been reported for feed preference of pigs fed a traditional U.S. 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, 2 experiments were conducted to test the hypothesis that feed preference and growth performance of weanling pigs will not differ if hybrid rye replaces a portion of corn in diets.

Materials and Methods

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

Animals, housing, experimental design

Experiment 1

Forty barrows with an initial body weight of 9.2 ± 1.0 kg at approximately 3 wk post-weaning were housed for 8 d in pens with slatted floors, a nipple waterer, and 2 identical plastic feeders attached to the front gate of each pen. There were 2 pigs per pen, for a total of 20 pens. Two experimental diets were formulated (Table 5.1). One diet containing corn as the exclusive cereal grain was formulated to meet or exceed the estimated requirements for standardized ileal digestible amino acids, vitamins, and minerals for 7 to 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. The same source of hybrid rye as used in chapter 3 was used in the present experiments. All pigs had *ad libitum* access to the corn diet in one feeder and to the corn-hybrid rye diet in the second feeder. The positions of the 2 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.

Experiment 2

A total of 160 pigs with an initial body weight of 6.0 ± 0.7 kg were weaned at 19 to 21 d of age were randomly allotted to 5 dietary treatments in a completely randomized design. Forty pens were used with 4 pigs per pen and 8 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 d, and a 3-phase feeding program was used. Phase 1 diets were fed for 7 d post-weaning, phase 2 diets were fed from day 7 to 21, and phase 3 diets were fed from day 21 to 34. In total, 15 diets were formulated (Table 5.2), 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 4 diets within each phase contained increasing levels of hybrid rye, which was included at the expense of corn. The same source of hybrid rye as was used in experiment 1 was also used in experiment 2. In phase 1, the replacement rate of corn for hybrid rye was 0, 7.5, 15.0, 22.5, or 30.0%, respectively. In phase 2, the replacement rate of corn for hybrid rye in each diet was 0, 10.0, 20.0, 30.0, or 40.0%, respectively, and in phase 3, the replacement rate of corn for hybrid rye in each diet was 0, 25.0, 50.0, 75.0, or 100.0%. 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 3 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 as well as 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 2 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 1 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 2 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, and transported to the University of Illinois Veterinary Medicine Diagnostic Laboratory 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 4,000 × *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 at the University of Illinois Veterinary Medicine Diagnostic Laboratory using a Beckman Coulter Clinical Chemistry AU analyzer (Beckman Coulter Inc., Brea, CA, USA).

Diet analyses

All 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 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 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. 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].

The corn used in the experiments was analyzed for mycotoxin concentrations by Trilogy Analytical Laboratories (Washington, MO, USA) using liquid chromatography-tandem mass spectroscopy. The detection limit was 0.1 mg/kg for deoxynivalenol, fumonisin (B1, B2, and B3) fusarenon X, and nivalenol. The detection limit for citrinin and diacetoxyscirpenol was 0.05 mg/kg. The detection limit was 0.02 mg/kg for neosolaniol, 0.0125 mg/kg for zearalenone, and 0.005 mg/kg for HT-2 toxin and T-2 toxin. The detection limit for ochratoxin A and aflatoxin (B1, B2, G1, and G2) was 0.001 mg/kg.

Calculations and statistical analyses

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-d 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., Cary, NC, USA). 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 $P \leq 0.05$ and considered a trend at $0.05 < P \leq 0.10$.

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 3 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). Data were analyzed using SAS 9.4 (SAS Institute Inc., Cary, NC, USA). 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 replicate. 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 to 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 $P \leq 0.05$ and considered a trend at $0.05 < P \leq 0.10$.

Results

The chemical composition of diets in both experiments were within expected ranges (Tables 5.1 and 5.3). The corn used in experiment 1 and in phase 1 diets of experiment 2 contained levels of mycotoxins below the minimum detection level, but 0.2 mg/kg of deoxynivalenol and 0.2 mg/kg fumonisin B1 were detected in corn used in phase 2 and 3 diets.

In experiment 1, feed 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, 8, and for the overall period (Table 5.4). No differences in feed disappearance were observed on day 1, day 5, or day 7, but there was a tendency ($P < 0.10$) for greater preference for the corn diet on day 4. Overall, pigs preferred ($P < 0.05$) 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 5.5). During phase 3 and overall, ADFI increased (quadratic, $P < 0.05$) as hybrid rye inclusion in the diet increased because pigs fed the diet with 100% hybrid rye replacement 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 5.6). However, diarrhea incidence decreased with 6 and 9% hybrid rye inclusion in phase 1, but not with 12% hybrid rye inclusion (quadratic, $P < 0.05$), and a tendency for reduced diarrhea incidence (linear, $P < 0.05$) was observed for the overall experiment as inclusion of hybrid rye increased in the diets.

As hybrid rye inclusion in diets increased, a trend was observed for increased concentration of red blood cells on day 21 (linear, $P < 0.10$), and red blood cell concentrations were greater (linear, $P < 0.05$) on day 34 with greater inclusion of hybrid rye in diets as well (Tables 5.7 and 5.8). Mean corpuscular volume and mean corpuscular hemoglobin were reduced (linear, $P < 0.05$) at the end of phase 3 as hybrid rye inclusion in diets increased. The concentration of total white blood cells did not differ among treatments on day 21, but total white blood cells tended to decrease and then increase (quadratic, $P < 0.10$) in pigs on day 34 as dietary concentration of hybrid rye increased. The concentration of neutrophils exhibited a quadratic response where concentrations were reduced, but then increased, as hybrid rye inclusion in the diet increased (day 21, P < 0.10; day 34, P < 0.05). At the conclusion of phase 2, tendencies (linear, $P < 0.10$) for increased concentrations of lymphocytes and reduced concentrations of eosinophils and basophils were observed as hybrid rye was added to the diet. Blood urea N increased ($P < 0.05$) as hybrid rye inclusion in the diet increased (day 21, quadratic; day 34, linear), but no differences were observed at either time point for serum albumin or total protein.

Discussion

Limited data have been published for growth performance of pigs fed hybrid rye (Schwarz et al., 2015; 2016; Bussières, 2018; Smit et al., 2019; Chuppava et al., 2020; Ellner et al., 2020; Wilke et al., 2020), and to our knowledge, there are no published data comparing the growth performance of nursery pigs fed diets containing corn or hybrid rye. Historically, rye has not been included in swine diets in large amounts due to concerns about ergot contamination and anti-nutritional factors (Friend and MacIntyre, 1969; Antoniou et al., 1981; Bederska-Lojewska 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). Additionally, preconceptions exist among livestock farmers that rye grain has poor palatability (e.g., Brooks, 1911; Halpin et al., 1936; Sharma et al., 1981), but there is scarce scientific evidence to support claims that feed preference for rye is inherently low in pigs.

When tested against a reference diet based on white rice, soybean meal, and wheat bran, preference for diet by 17-kg pigs did not differ from 50% when rye was fed as 100% of the diet (Solà-Oriol et al., 2009a). At 60% inclusion rate, preference for rye was reduced compared with the reference diet, but at 30% inclusion rate, pigs showed no preference for the rye diet or the reference diet. Preference for one source of corn was reduced at all inclusion rates in the aforementioned experiment, but a second source of corn elicited more erratic preference rates of 31, 8, and 65% when fed as 30, 60, or 100% of the diet and compared against the white rice reference diet. Overall, results of the experiment indicated that the preference for corn or rye did not differ in nursery pigs. In another two-way choice experiment by the same authors, preference for rye did not differ from preference for white rice when rye was fed at 50% inclusion in the diet (Solà-Oriol, 2009b). Oddly, the pigs' preference toward rye was reduced when fed at 25% or 100% inclusion. Results of the present experiment and of the work by Solà-Oriol et al. (2009a; 2009b) indicate preference for cereal grains in nursery pigs fluctuates with dietary inclusion rate, but that young pigs do not have an inherent aversion to consuming rye compared with corn. Although pigs in experiment 1 had slightly reduced preference (43.4% versus 56.6%) for the diet containing 26.5% hybrid rye compared with corn when given the choice, feed intake was not hindered when hybrid rye was offered to nursery pigs as the singular dietary option in experiment 2.

A paucity of information exists about replacing corn with hybrid rye in diets for weanling or nursery pigs, but results of several experiments have demonstrated that replacing wheat with hybrid rye does not influence growth performance (Chuppava et al., 2020; Ellner et al., 2020; Wilke et al., 2020). In earlier experiments with non-hybrid rye, feed intake and growth appeared to be compromised when rye replaced barley in diets for weanling pigs (Bedford et al., 1992) and for 17-kg pigs (Thacker et al., 1999). In slightly larger pigs, ADG and G:F were reduced when individually-housed pigs were fed diets containing 27% population rye at the expense of wheat during the initial 14 d 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). However, no reduction in feed intake as a result of hybrid rye inclusion in the diet was observed in the present experiment, indicating the stepwise introduction of hybrid rye to diets after weaning was likely an effective strategy at acclimating the pigs to the novel ingredient. It is also possible the young pigs in the present experiment were not consuming feed in large enough quantities to be restricted by dietary fiber and physical gut fill, which may be of greater importance for growing and finishing pigs. Gain:feed was reduced when greater amounts of hybrid rye were fed, but this was unsurprising as 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 rye-containing diets.

In growing pigs, the dietary fiber from hybrid rye is more fermentable than 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 (Karppinen et al., 2003; 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, likely as a result of greater lactic acid and butyrate concentrations in the hindgut (Chuppava et al., 2020). Therefore, despite having limited fermentative capacity 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. On the contrary, hybrid rye has more total amino acids and reduced standardized ileal digestibility of amino acids compared with corn, which, in turn, results in more undigested amino acids entering the hindgut of pigs (McGhee and Stein, 2018). Pigs are particularly susceptible to gastrointestinal distress immediately after weaning, and 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 (Ball and Aherne, 1987; Lallès et al., 2004; Montagne et al., 2004; Wellock et al., 2008; Heo et al., 2009; Gloaguen et al., 2014).

Despite elevated dietary fiber and N in hybrid rye, our hypothesis that growth performance would not be diminished by replacement of corn with hybrid rye in diets for nursery pigs was ultimately supported. A reduction in the incidence of diarrhea was also observed in phase 1 with modest inclusion of hybrid rye (6 or 9%), which may be a reflection of improved intestinal health as a result of fiber fermentation. Similarly, the concentration of neutrophils were reduced for the modest hybrid rye treatments on day 21 and 34, which may indicate reduced innate immune system activation and inflammation in those groups of pigs (Fournier and Parkos, 2012). Butyrate promotes regulatory T-cell synthesis in the large intestine (Kespohl et al., 2017), and in the present experiment, total lymphocytes tended to linearly increase with greater concentrations of hybrid rye in the diet. In an experiment where dogs were fed supplemental fructooligosaccharides (which are present in large amounts in hybrid rye) and mannanoligo-saccharides, reduced neutrophils and elevated lymphocytes were also observed (Swanson et al., 2002). Neutrophil release into the blood is modulated by cytokines and chemokines, and T-cells are a key producer of cytokines; thus, changes in blood cell concentrations in the present experiment indicate that concentrations of blood cytokines may also be observed in pigs fed hybrid rye. Based on the conflicting nature of both prebiotic dietary fiber and excess protein being present in hybrid rye, the health impacts of feeding the ingredient to pigs after weaning warrants more investigation, especially under the stressors present at commercial farms.

Conclusions

Nursery pigs preferred diets containing corn to diets containing hybrid rye 56.6% of the time when given the choice between 2 diets, but when singular experimental diets were offered to pigs, overall ADFI was greater as the inclusion of hybrid rye in the diet increased. Consequently, overall G:F was reduced for the greatest inclusion of dietary hybrid rye, which was a result of reduced metabolizable energy in hybrid rye compared with corn. Replacing up to 30, 40, and 100% of the corn in phase 1, 2, and 3 nursery diets, respectively, did not affect body weights or ADG of pigs during the experiment. The incidence of diarrhea was reduced in the first week after weaning when 6 or 9% hybrid rye was fed, and differences in blood cell concentrations indicate 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 first 3 weeks after weaning without compromising growth.

Tables

Table 5.1. Composition of diets in experiment 1 (as-is basis)

Item	Control	Hybrid rye
Ingredient, %		
Ground hybrid rye	-	26.20
Ground corn	52.37	26.20
Soybean meal	24.50	24.50
Whey, dried	12.00	12.00
Fish meal	6.00	6.00
Soybean oil	3.00	3.00
Ground limestone	0.88	0.93
Dicalcium phosphate	0.25	0.15
L-lysine HCl, 78%	0.35	0.34
DL-methionine, 98%	0.11	0.13
L-threonine, 98%	0.09	0.10
Sodium chloride	0.30	0.30
Vitamin-mineral premix[1]	0.15	0.15
Analyzed composition		
Dry matter, %	88.38	88.71
Ash, %	6.05	5.37
Gross energy, kcal/kg	4,053	4,001
Metabolizable energy[2], kcal/kg	3,456	3,396
Starch, %	34.17	28.15

Table 5.1 (cont.)

Item	Control	Hybrid rye
Insoluble dietary fiber, %	10.80	11.00
Soluble dietary fiber, %	1.20	2.00
Total dietary fiber, %	12.00	13.00
Acid-hydrolyzed ether extract, %	5.38	5.54
Crude protein, %	20.16	20.24
Arg, %	1.33	1.20
His, %	0.53	0.49
Ile, %	0.98	0.91
Leu, %	1.75	1.56
Lys, %	1.48	1.51
Met, %	0.45	0.45
Cys, %	0.31	0.31
Phe, %	1.03	0.95
Thr, %	0.87	0.88
Trp, %	0.26	0.27
Val, %	1.05	1.00

[1]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

Table 5.1 (cont).

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.

[2]Metabolizable energy was calculated based on the value 3,150 kcal/kg metabolizable energy in hybrid rye (McGhee and Stein, 2020), and values for all other ingredients according to NRC (2012).

Table 5.2. Ingredient composition of diets with increasing rate of hybrid rye replacement for corn, experiment 2 (as-is basis)

	Phase 1 (day 1 – 7)[1]					Phase 2 (day 7 – 21)[1]					Phase 3 (day 21 – 34)[1]				
Item, %	0%	7.5%	15%	22.5%	30%	0%	10%	20%	30%	40%	0%	25%	50%	75%	100%
Ground hybrid rye	-	3.00	6.00	9.00	12.00	-	5.34	10.68	16.03	21.36	-	15.07	30.16	45.25	60.34
Ground corn	39.96	36.99	33.98	30.98	27.98	53.40	48.07	42.74	37.39	32.07	60.28	45.24	30.16	15.09	-
Whey, dried	25.00	25.00	25.00	25.00	25.00	12.00	12.00	12.00	12.00	12.00	-	-	-	-	-
Soybean meal	20.00	20.00	20.00	20.00	20.00	24.50	24.50	24.50	24.50	24.50	35.00	35.00	35.00	35.00	35.00
Fish meal	8.00	8.00	8.00	8.00	8.00	6.00	6.00	6.00	6.00	6.00	-	-	-	-	-
Blood plasma	3.50	3.50	3.50	3.50	3.50	-	-	-	-	-	-	-	-	-	-
Soybean oil	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Limestone	0.76	0.74	0.74	0.74	0.74	0.87	0.87	0.88	0.89	0.91	0.86	0.91	0.95	0.98	1.03
Dicalcium phosphate	-	-	-	-	-	0.25	0.23	0.21	0.19	0.17	1.05	0.97	0.90	0.85	0.78
L-lysine HCl, 78%	0.21	0.20	0.20	0.20	0.20	0.34	0.34	0.34	0.34	0.33	0.25	0.24	0.24	0.23	0.22
DL-methionine, 98%	0.09	0.09	0.10	0.10	0.10	0.10	0.11	0.11	0.12	0.12	0.06	0.07	0.08	0.09	0.11
L-threonine, 98%	0.03	0.03	0.03	0.03	0.03	0.09	0.09	0.09	0.09	0.09	0.05	0.05	0.06	0.06	0.07
Salt	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Vitamin-mineral premix[2]	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15

Table 5.2 (cont.)

[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.

Table 5.3. Analyzed composition of diets with increasing rate of hybrid rye replacement for corn, experiment 2 (as-is basis)

	Phase 1 (day 1 – 7)[1]					Phase 2 (day 7 – 21)[1]					Phase 3 (day 21 – 34)[1]				
Item	0%	7.5%	15%	22.5%	30%	0%	10%	20%	30%	40%	0%	25%	50%	75%	100%
Dry matter, %	89.13	89.18	89.06	89.12	89.15	87.91	88.41	88.11	88.32	88.39	87.32	87.19	87.34	87.47	87.20
Ash, %	6.09	6.33	5.89	6.34	6.21	5.06	5.60	5.48	5.58	5.91	4.85	4.68	4.40	4.76	4.63
Gross energy, kcal/kg	4,029	4,016	4,028	4,025	4,011	4,011	3,999	3,991	4,012	3,983	3,963	3,963	3,946	3,953	3,933
ME[2], kcal/kg	3,460	3,454	3,446	3,439	3,432	3,409	3,397	3,384	3,371	3,359	3,367	3,332	3,296	3,260	3,223
Starch, %	19.87	20.19	21.83	23.96	19.75	33.02	30.11	28.78	28.70	24.71	32.33	26.70	28.85	32.57	27.20
Crude protein, %	23.37	23.57	22.94	22.88	22.58	20.25	20.86	21.09	21.23	21.95	20.18	21.34	21.53	22.41	22.43
Insoluble dietary fiber, %	8.50	8.40	8.10	8.60	8.60	9.20	9.00	9.70	9.90	10.30	11.30	12.30	12.40	13.30	14.70
Soluble dietary fiber, %	0.60	0.80	1.50	1.00	1.00	0.80	2.10	1.50	1.70	1.50	1.70	1.50	1.80	2.80	2.80
Total dietary fiber, %	9.10	9.20	9.60	9.60	9.60	10.00	11.10	11.20	11.60	11.80	13.00	13.90	14.20	16.00	17.60
AEE[3], %	4.45	4.46	4.85	4.26	4.05	5.12	4.94	4.90	4.98	4.90	5.09	4.79	3.26	3.14	2.50
Arg, %	1.25	1.29	1.29	1.26	1.38	1.18	1.24	1.20	1.40	1.30	1.25	1.45	1.51	1.40	1.44
His, %	0.53	0.55	0.54	0.54	0.58	0.48	0.50	0.48	0.55	0.52	0.50	0.57	0.58	0.55	0.55
Ile, %	0.99	1.00	1.00	1.00	1.05	0.88	0.94	0.85	1.02	0.99	0.87	1.03	1.05	0.98	1.00
Leu, %	1.85	1.89	1.86	1.84	1.94	1.59	1.67	1.52	1.76	1.69	1.62	1.81	1.79	1.67	1.65

Table 5.3 (cont.)

Item	Phase 1 (day 1 – 7)[1]					Phase 2 (day 7 – 21)[1]					Phase 3 (day 21 – 34)[1]				
	0%	7.5%	15%	22.5%	30%	0%	10%	20%	30%	40%	0%	25%	50%	75%	100%
Lys, %	1.56	1.67	1.62	1.72	1.65	1.30	1.40	1.34	1.54	1.51	1.23	1.42	1.51	1.39	1.46
Met, %	0.45	0.42	0.45	0.45	0.47	0.43	0.41	0.38	0.57	0.45	0.33	0.40	0.40	0.40	0.41
Cys, %	0.37	0.42	0.39	0.37	0.40	0.29	0.29	0.25	0.33	0.31	0.28	0.34	0.36	0.35	0.35
Phe, %	1.01	1.05	1.05	1.04	1.12	0.92	0.98	0.90	1.07	1.03	0.97	1.14	1.17	1.08	1.13
Thr, %	0.97	1.01	1.00	0.99	1.04	0.77	0.82	0.77	0.90	0.88	0.75	0.85	0.93	0.85	0.88
Trp, %	0.29	0.28	0.30	0.29	0.30	0.24	0.24	0.23	0.24	0.24	0.23	0.25	0.25	0.26	0.27
Val, %	1.15	1.18	1.17	1.16	1.22	0.95	1.01	0.95	1.11	1.07	0.94	1.09	1.12	1.06	1.08

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

[2]ME = metabolizable energy. Calculated concentration of ME was 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).

[3]AEE = acid-hydrolyzed ether extract.

Table 5.4. Daily and overall feed disappearance and feed preference in experiment 1[1]

Item	Control	Hybrid rye	SD	*P*-value
Feed disappearance, kg				
Day 1	0.83 ± 0.11	0.77 ± 0.13	-	0.282
Day 2	1.04 ± 0.10	0.65 ± 0.10	-	<0.001
Day 3	0.97 ± 0.04	0.66 ± 0.08	-	<0.001
Day 4	0.89 ± 0.03	0.80 ± 0.05	-	0.083
Day 5	1.19 ± 0.24	1.09 ± 0.22	-	0.216
Day 6	1.46 ± 0.26	1.10 ± 0.18	-	0.014
Day 7	1.19 ± 0.19	0.99 ± 0.24	-	0.141
Day 8	1.38 ± 0.20	0.99 ± 0.23	-	0.016
Overall	8.95 ± 4.26	7.06 ± 4.70	-	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

[1]Means represent 20 observations.

Table 5.5. Growth performance of pigs fed diets with increasing rate of hybrid rye replacement for corn, experiment 2[1]

	Phase 3 corn replacement rate[2]						*P* – values	
Item	0%	25%	50%	75%	100%	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, kg								
Phase 1, day 1 to 7	0.078	0.084	0.073	0.080	0.095	0.015	0.553	0.531
Phase 2, day 7 to 21	0.226	0.236	0.232	0.225	0.256	0.016	0.342	0.549
Phase 3, day 21 to 34	0.522	0.535	0.527	0.509	0.495	0.020	0.214	0.405
Overall, day 1 to 34	0.309	0.319	0.312	0.304	0.314	0.013	0.938	0.984
Average daily feed intake, kg								
Phase 1, day 1 to 7	0.130	0.138	0.121	0.118	0.141	0.012	0.936	0.360
Phase 2, day 7 to 21	0.343	0.333	0.334	0.330	0.351	0.020	0.842	0.449

Table 5.5 (cont.)

	Phase 3 corn replacement rate[2]						*P* – values	
Item	0%	25%	50%	75%	100%	SE	Linear	Quadratic
Average daily feed intake, kg								
Phase 3, day 21 to 34	0.802	0.761	0.770	0.766	0.871	0.030	0.134	0.016
Overall, day 1 to 34	0.475	0.458	0.457	0.454	0.507	0.018	0.291	0.042
Gain:feed								
Phase 1, day 1 to 7	0.556	0.599	0.571	0.669	0.626	0.086	0.446	0.885
Phase 2, day 7 to 21	0.658	0.714	0.693	0.680	0.727	0.021	0.129	0.905
Phase 3, day 21 to 34	0.654	0.700	0.687	0.664	0.580	0.023	0.018	0.004
Overall, day 1 to 34	0.652	0.695	0.685	0.670	0.624	0.020	0.204	0.019

[1]Least square means represent 8 observations.

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

Table 5.6. Average fecal scores and incidence of diarrhea in pigs fed diets with increasing rate of hybrid rye replacement for corn, experiment 2[1]

	Phase 3 corn replacement rate						*P* – values	
Item	0%	25%	50%	75%	100%	SE	Linear	Quadratic
Average fecal score[2]								
Phase 1, day 1 to 7	2.37	2.62	2.06	1.94	2.38	0.174	0.225	0.221
Phase 2, day 7 to 21	2.59	2.85	2.68	2.40	2.76	0.141	0.861	0.816
Phase 3, day 21 to 34	1.93	2.00	1.84	1.96	1.94	0.101	0.944	0.798
Overall, day 1 to 34	2.28	2.46	2.22	2.13	2.36	0.091	0.571	0.487
Diarrhea incidence[3], %								
Phase 1, day 1 to 7	45.83	58.33	16.67	12.50	45.83	10.170	0.106	0.024
Phase 2, day 7 to 21	42.86	58.93	44.64	26.79	51.79	6.677	0.457	0.531
Phase 3, day 21 to 34	7.14	12.50	7.14	3.57	5.36	4.419	0.278	0.809
Overall, day 1 to 34	28.68	39.71	24.26	14.71	31.62	4.196	0.090	0.144

[1]Least square means for dietary treatments represent 8 observations.

[2]Fecal scores: 1 = normal feces; 2 = moist feces; 3 = mild diarrhea; 4 = severe diarrhea; and 5 = watery diarrhea.

[3]Incidence of diarrhea calculated as number of days with fecal score ≥ 3 divided by total number of observations.

Table 5.7. Day 21 blood analyses from pigs fed diets with increasing rate of hybrid rye replacement for corn, experiment 2[1]

	Phase 3 corn replacement rate[2]						*P* – values	
Item	0%	25%	50%	75%	100%	SE	Linear	Quadratic
Red blood cells, × 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[3], pg	16.03	15.44	15.45	15.44	15.04	0.525	0.242	0.860
MCHC[3], g/dL	30.16	30.01	30.45	30.10	29.91	0.220	0.560	0.304
Platelets, × 10^5/µL	5.43	6.22	6.67	5.74	6.53	0.630	0.346	0.508
Total white blood cells[4], × 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

Table 5.7 (cont.)

	Phase 3 corn replacement rate[2]						*P* – values	
Item	0%	25%	50%	75%	100%	SE	Linear	Quadratic
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

[1]Least square means for dietary treatments represent 8 observations.

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

[3]MCH = Mean corpuscular hemoglobin; MCHC = Mean corpuscular hemoglobin concentration.

Table 5.8. Day 34 blood analyses from pigs fed diets with increasing rate of hybrid rye replacement for corn, experiment 2[1]

	Phase 3 corn replacement rate[2]						*P* – values	
Item	0%	25%	50%	75%	100%	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[3], pg	17.41	17.34	17.16	16.80	15.75	0.439	0.009	0.202
MCHC[3], 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[4], $\times 10^3$/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

Table 5.8 (cont.)

	Phase 3 corn replacement rate[2]						*P* – values	
Item	0%	25%	50%	75%	100%	SE	Linear	Quadratic
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

[1]Least square means for dietary treatments represent 8 observations.

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

[3]MCH = Mean corpuscular hemoglobin; MCHC = Mean corpuscular hemoglobin concentration.

[4]The concentration of basophils in blood samples was excluded from the table because the variable did not follow a normal distribution.

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CHAPTER 6: Weanling pigs consume more feed if hybrid rye replaces corn in diets, but average daily gain and fecal scores are not impacted by hybrid rye

Abstract

An experiment was conducted to test the hypothesis that growth performance and health status of pigs will not be impeded if greater concentrations of hybrid rye than previously tested are included in diets at the expense of corn during the initial 5 wk post-weaning. A total of 128 weanling pigs (5.6 ± 0.5 kg) were randomly allotted to 32 pens and 4 dietary treatments. Pigs were fed experimental diets for 35 d in 3 phases with day 1 to 7 being phase 1, day 7 to 21 being phase 2, and day 21 to 35 being phase 3. Within each phase, a control diet primarily based on corn and soybean meal was formulated, and 3 additional diets in which 8.0, 16.0, or 24.0% (phase 1), 16.0, 32.0, or 48.0% (phase 2), and 20.0, 40.0, or 60.3% (phase 3) hybrid rye was added to the control diet at the expense of corn were formulated as well. Individual pig weights were recorded at the start and conclusion of each phase, fecal scores were visually assessed every other day on a pen basis, and blood samples were obtained from 1 pig per pen on days 21 and 35. Results indicated that average daily gain (ADG) in phase 1 increased (linear, $P < 0.05$) as the inclusion of hybrid rye increased, but there were no other differences in body weights or ADG during the experiment. Average daily feed intake linearly increased in phase 1, phase 3, and overall ($P < 0.05$) as hybrid rye inclusion increased in the diets. Thus, gain:feed was negatively impacted by inclusion of hybrid rye in the diet (phase 1, linear, $P < 0.05$; phases 2, 3, and overall, quadratic, $P < 0.05$). No differences in average fecal scores or diarrhea incidence were

observed. Day 21 and 35 blood urea N increased (linear, $P < 0.05$) as hybrid rye increased in the diets, and day 21 serum total protein also increased (linear, $P < 0.05$) with increasing hybrid rye inclusion in the diet. In conclusion, ADG of pigs was not different among treatments when hybrid rye was included in nursery diets at the expense of corn, but pigs consumed more feed to compensate for the reduced metabolizable energy of hybrid rye compared with corn. Diarrhea incidence was not influenced by hybrid rye inclusion in the present experiment, but differences in concentrations of white blood cells and blood serum cytokines indicate that the immune system was affected differently when hybrid rye instead of corn was fed to nursery pigs.

Key words: cereal grains, corn, growth performance, hybrid rye, small grains

Abbreviations

ADFI	average daily feed intake
ADG	average daily gain
G:F	gain:feed
IFNγ	interferon gamma
IgG	immunoglobulin G
IL	interleukin
IL-1RA	interleukin-1 receptor antagonist
TNF-α	tumor necrosis factor-α

Introduction

In a previous experiment, no differences in final body weights were observed when hybrid rye was fed to nursery pigs at inclusion rates up to 12, 21, and 60% in phases 1 (day 1 to 7 post-weaning), 2 (day 7 to 21 post-weaning), and 3 (day 21 to 35 post-weaning), respectively

(McGhee and Stein, 2021). Average daily feed intake (**ADFI**) was not affected until phase 3, at which point feed intake quadratically increased as hybrid rye in the diet increased. Based on these results, it was hypothesized that greater inclusion rates of hybrid rye may be used in phases 1 and 2 without negatively impacting growth performance. Hybrid rye contains more dietary fiber than corn, and in growing pigs, the fermentability of dietary fiber from hybrid rye was greater than the fermentability of dietary fiber from corn (McGhee and Stein, 2020). Fermentation of arabinoxylans and fructooligosaccharides, which are abundant in hybrid rye, increases the proportion of beneficial bacteria (bifidobacteria and lactobacilli) in the hindgut of monogastric animals (Hughes et al., 2007; Bouhnik et al., 2007; Bach Knudsen and Lærke, 2010; Schokker et al., 2018). Consuming rye also increases the quantity of butyrate and the proportion of butyrate in total volatile fatty acids in the colon (Bach Knudsen et al., 1991; 2005; Bach Knudsen and Lærke, 2010). Butyrate has anti-inflammatory and anticarcinogenic effects in the colon, as well as the potential to improve gut barrier integrity (Hamer et al., 2008; Vogt et al., 2014). In the previous experiment, a reduction in the incidence of diarrhea was observed in the first week after weaning when small amounts of hybrid rye were included in the diet, and differences in blood characteristics were observed among treatments. Therefore, it was also hypothesized for the present experiment that feeding greater amounts of hybrid rye at the expense of corn may beneficially influence health parameters.

Materials and Methods

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

Animals, housing, and experimental design

A total of 128 pigs that were the offspring of Line 359 boars and Camborough sows (Pig Improvement Company, Henderson, TN, USA) with an initial body weight of 5.6 ± 0.5 kg were weaned at 19 to 21 d of age and allotted to 4 treatment groups. Thirty-two pens were used with 4 pigs per pen and 8 replicate pens per treatment group. Sex was balanced among pens and treatment groups. 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 to the pigs on an *ad libitum* basis.

Pigs were fed experimental diets for 35 d and a 3-phase feeding program was used. Phase 1 diets were fed for 7 d post-weaning, phase 2 diets were fed from day 7 to 21, and phase 3 diets were fed from day 21 to 35. A total of 12 diets were formulated (Table 6.1), and all diets were fed in mash form. In each phase, a control diet primarily based on corn and soybean meal was formulated, in addition to 3 diets with increasing concentrations of hybrid rye in place of corn. The same source of hybrid rye as used in chapter 3 was used in the present experiment. In phase 1, the inclusion rate of hybrid rye in each diet was 0, 8.0, 16.0, or 24.0%, respectively. In phase 2, the inclusion rate of hybrid rye in each diet was 0, 16.0, 32.0, or 48.0%, respectively, and in phase 3, the inclusion rate of hybrid rye in each diet was 0, 20.0, 40.0, or 60.3%. 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 3 phases (NRC, 2012). However, diets were not formulated to be isocaloric or isonitrogenous; therefore, as hybrid rye inclusion rate increased within phases, the calculated concentrations of total dietary fiber and crude protein increased, whereas the concentration of metabolizable energy decreased.

Individual pig weights were recorded 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 was recorded. Fecal scores were assessed visually for each pen as a whole every other day by 2 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).

Blood sample collection and analyses

Two 3-mL blood samples were collected from the jugular vein from 1 pig per pen on the last day of phase 2, as well as 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 2 samples of blood obtained per pig, one was collected in a vacutainer tube containing ethylenediamine-tetraacetic acid as an anti-coagulant, immediately placed on ice, and transported to the University of Illinois Veterinary Medicine Diagnostic Laboratory for complete blood cell 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 serum vacutainer tube containing spray-dried silica as a clot activator, allowed to clot, and centrifuged at 4,000 × *g* for 13 min at room temperature. Serum was removed from centrifuged tubes and stored at −20 °C until analysis. Total protein, blood urea N, and albumin were analyzed at the University of Illinois Veterinary Medicine Diagnostic Laboratory using a Beckman Coulter Clinical Chemistry AU analyzer (Beckman Coulter Inc., Brea, CA, USA). The concentration of immunoglobulin G (**IgG**) in 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-1RA**), IL-2, IL-4, IL-6, IL-8, IL-10, IL-12, IL-18, interferon gamma (**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).

Chemical analyses

Diet samples were analyzed for dry matter by oven drying at 135 °C for 2 h (method 930.15; AOAC Int., 2007). These 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 protein was calculated as N × 6.25. 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 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. 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].

The corn used in the experiment was analyzed for mycotoxins by Trilogy Analytical Laboratories (Washington, MO, USA) using liquid chromatography-tandem mass spectroscopy. The detection limit was 0.1 mg/kg for 15-acetyl deoxynivalenol, 3-acetyl deoxynivalenol, deoxynivalenol, fumonisin (B1, B2, and B3), fusarenon X, and nivalenol. Citrinin and diacetoxyscirpenol had a detection limit of 0.05 mg/kg, neosolaniol had a detection limit of 0.02 mg/kg. The detection limit of zearalenone was 0.0125 mg/kg, and the detection limits of HT-2 and T-2 toxins were 0.005 mg/kg. The following mycotoxins had the detection limit of 0.001 mg/kg: aflatoxin (B1, B2, G1, and G2) and ochratoxin A.

Calculations and statistical analyses

Pen was considered the experimental unit, and data were summarized for each treatment group. Average daily gain (**ADG**), average daily feed intake, gain:feed (**G:F**), average fecal scores, and diarrhea frequency were calculated for each of the 3 phases as well as for the entire experiment. If a pig was removed from a pen during the experiment, ADG, ADFI and G:F 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). Normality of the 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, 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 replicate. Least square means were calculated for each treatment group using the LSMEANS statement in PROC MIXED. Contrast statements were used to test for linear and quadratic effects of including graded levels of hybrid rye to 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 $P \leq 0.05$ and considered a trend at $0.05 < P \leq 0.10$.

Results

The chemical compositions of diets were within expected ranges (Table 6.2). The corn used for phase 1 diets contained no detectable mycotoxins; however, 0.2 mg/kg fumonisin B1, 0.2 mg/kg deoxynivalenol, 0.03 mg/kg zearalenone, and 0.01 mg/kg HT-2 toxin were detected in corn fed during phase 2 and 3.

The body weight of pigs at the end of phase 1, phase 2, and phase 3 was not influenced by dietary treatment (Table 6.3). Average daily gain in phase 1 linearly increased ($P < 0.05$) as the inclusion of hybrid rye increased, but ADG in phase 2 and phase 3 was not impacted by treatment. Average daily feed intake linearly increased ($P < 0.05$) during phase 1, phase 3, and overall as hybrid rye was added to the diets. However, G:F increased (linear, $P < 0.05$) in phase 1 as the concentration of hybrid rye in the diet increased, but in phase 2, phase 3, and for the overall period, G:F was reduced as hybrid rye inclusion in diets increased (quadratic, $P < 0.05$). No differences in average fecal scores nor diarrhea incidence were observed (Table 6.4).

Day 21 and 35 blood urea N linearly increased ($P < 0.05$) as hybrid rye was added to the diets, and day 21 serum total protein also linearly increased ($P < 0.05$) with hybrid rye inclusion (Table 6.5 and 6.6). The concentration of red blood cells and hemoglobin in the blood was not affected by diet, but mean corpuscular hemoglobin concentration was reduced (quadratic, $P < 0.05$) as hybrid rye concentration in diets increased on day 35. Neutrophils tended to increase with increased hybrid rye inclusion in the diet on day 21 (linear, $P < 0.10$) and 35 (quadratic, $P < 0.10$). Eosinophils on day 21 tended to be greater for pigs fed the phase 2 diet containing 16% hybrid rye than for pigs fed the diet without hybrid rye or diets with 32 or 48% hybrid rye ($P < 0.10$). Lymphocytes on day 35 tended to increase and then decrease as hybrid rye in the diet increased ($P < 0.10$).

In serum from pigs on day 21, the concentration of IL-1β linearly increased ($P < 0.05$) and IL-1RA tended to increase (linear, $P < 0.10$) with greater inclusion of hybrid rye in the diet (Table 6.7). The concentration of IL-2 and IL-10 decreased and then increased on day 21 as hybrid rye inclusion in the diet increased ($P < 0.05$). On day 35, the concentration of IL-1RA tended to increase and then decrease with greater hybrid rye in the diet (quadratic, $P < 0.10$), and IL-8, IL-12, and IFN-γ increased and then decreased (quadratic, $P < 0.05$) as hybrid rye in diets increased.

Discussion

Hybrid rye is a cereal grain with similar nutrient composition to wheat and barley, in the sense that hybrid rye, wheat, and barley all contain approximately 10 to 12% crude protein, 1 to 2% lipid, 1 to 3% ash, 55 to 65% starch, and 10 to 20% dietary fiber (McGhee and Stein, 2020). The dietary fiber in hybrid rye is not identical to wheat or barley, but each grain contains varying amounts of arabinoxylan, cellulose, mixed-linked ß-glucans, fructooligosaccharides, resistant starch, and lignin (McGhee and Stein 2018; 2020). In Europe and Canada, barley and wheat are staple feed ingredients for swine diets, and thus, it is reasonable to expect that replacing portions of wheat or barley with hybrid rye in diets for pigs will not result in differences in growth performance. This hypothesis has been confirmed in gestating and lactating sows (Sørensen and Krogsdahl, 2017), nursery pigs (Chuppava et al., 2020; Ellner et al., 2020; Wilke et al., 2020), and growing-finishing pigs (Schwarz et al., 2015; 2016; Bussières, 2018; Smit et al., 2019).

However, in the United States and many other parts of the world, corn is the dominant cereal grain fed to pigs, and effects of replacing corn with hybrid rye in diets for weanling pigs are not as easily predicted. Hybrid rye, due to reduced concentrations of lipid and starch, has less metabolizable energy than corn when fed to growing pigs (McGhee and Stein, 2020). Hybrid rye also has more total amino acids but reduced standardized ileal digestibility of amino acids compared with corn, which results in more undigested amino acids entering the large intestine (McGhee and Stein, 2018). More undigested protein reaching the hindgut of young pigs carries the potential to compromise intestinal health (Ball and Aherne, 1987; Lallès et al., 2004; Montagne et al., 2004; Wellock et al., 2008; Heo et al., 2009; Gloaguen et al., 2014). Conversely, the dietary fiber in hybrid rye is more fermentable than corn by growing pigs (McGhee and Stein, 2020), and hindgut fermentation of rye fiber may improve the intestinal health of humans and pigs (Karppinen et al., 2003; Bach Knudsen et al., 2005; Le Gall et al., 2009; Chuppava et al., 2020). However, soluble fiber, which is present in greater amounts in hybrid rye than in corn, may pose challenges to digestion in newly weaned pigs (Agyekum and Nyachoti, 2017).

Results of a previous experiment conducted at the University of Illinois indicated that average body weight, ADG, ADFI, and G:F were not impacted during the initial 3 wk post-weaning when modest amounts of hybrid rye (up to 12% from day 1 to 7 and up to 21% during the following 14 d) were fed at the expense of corn in diets for weanling pigs (McGhee and Stein, 2021). Therefore, it was hypothesized in the present experiment that growth performance would not be reduced if greater amounts of hybrid rye were included at the expense of corn in phase 1 and 2 diets for weanling pigs, and this hypothesis was supported by the data from the experiment. Similar to what was previously observed, no reduction in ADG or G:F was observed in the initial 3 wk of the present experiment. Unexpectedly, poor growth performance of pigs fed the control diet was observed in phase 1, but it is unlikely this observation can be fully attributed to diet. Nonetheless, average body weights, ADG, and ADFI did not differ in phase 2, indicating that whatever caused the initial stunted growth in phase 1 was overcome by day 21. In phase 3 (day 21 to 34) of the previous and present experiment, ADFI and G:F were increased and decreased, respectively, as hybrid rye inclusion in the diet increased to up to 60% of the diet, likely as a result of the reduced metabolizable energy of hybrid rye compared with corn. Although a reduction in the incidence of diarrhea was observed in the first phase of the previous experiment, no positive or negative impact of hybrid rye was observed for fecal scores or diarrhea incidence in the present experiment. The lack of differences observed for diarrhea frequency may signify the previous result was due to type I error, or the inherent differences in nursery barns, weaning groups, and pathogen loads of pigs in each experiment yielded different outcomes for diarrhea incidence.

Because differences in blood characteristics were observed in the previous experiment, it was hypothesized that differences among treatments would also be observed in the present experiment. As expected, blood urea N increased on both sampling days as the inclusion of hybrid rye in the diet increased, indicating greater amino acid catabolism and less efficient utilization of dietary protein (Waguespack et al., 2011; Millet et al., 2018). The tendency for elevated neutrophils in pigs fed greater amounts of hybrid rye may indicate a greater activation of the innate immune response; neutrophils defend against infections and produce inflammatory cytokines (Swanson et al., 2002). Likewise, IL-8, a neutrophil recruiter (Kucharzik et al., 2005), was also elevated on day 35 in pigs fed hybrid rye. In the previous experiment, neutrophils tended to be reduced among pigs fed the moderate hybrid rye diets, so it is possible that a small amount of hybrid rye in the diet for weanling pigs may reduce inflammation and immune system activation, but after a certain threshold, a trend for greater inflammation emerges. However, additional research is needed to confirm this hypothesis.

Microbial fermentation of rye fiber increases the quantity and proportion of butyrate in the hindgut, and butyrate exerts anti-inflammatory effects in the host (Hamer et al., 2008); however, most serum indicators of inflammation in the present experiment suggest the opposite was true for pigs fed greater amounts of hybrid rye. Indeed, pro-inflammatory cytokines IL-1β, IL-8, and IL-12 were greater in pigs fed greater amounts of hybrid rye, whereas anti-inflammatory cytokines IL-2 and IL-10 were reduced on at least one sampling day. If very large inclusions of hybrid rye are fed to young pigs with immature gastrointestinal tracts, it is possible the dietary fiber and undigested amino acids aggravate, rather than preserve, intestinal epithelium barrier function, thus promoting a pro-inflammatory response and immune system activation. Pro-inflammatory stress in livestock production is associated with economic loss because nutrient and energy utilization shifts away from body mass accretion and toward immune system function (Elsasser et al., 2008). However, growth rate and fecal scores of pigs fed varying levels of hybrid rye did not differ despite detectable differences in immune parameters in the present experiment, indicating the biological and economic significance of the changes in immune cell and cytokine concentrations are not clear. More research is warranted to investigate the effects of feeding large quantities of hybrid rye to newly weaned pigs on intestinal morphology and immune function, especially under challenged conditions.

Conclusions

It was hypothesized that hybrid rye may replace a majority of corn in diets for pigs without jeopardizing growth performance during the initial 5 wk post-weaning. Therefore, hybrid rye was included in nursery diets at inclusion rates up to 24, 48, and 60% in phase 1 (week 1), phase 2 (week 2 and 3), and phase 3 (week 4 and 5), respectively, and average body weights and ADG were not impacted by hybrid rye inclusion. As hybrid rye inclusion in the diet increased, ADFI increased and G:F was reduced, likely as a result of less metabolizable energy in hybrid rye than in corn. Differences in pro- and anti-inflammatory cytokine concentrations indicate pigs fed hybrid rye had altered immune responses compared with pigs fed corn, though the differences did not influence growth or incidence of diarrhea under the conditions of the present experiment.

Tables

Table 6.1. Ingredient composition of diets with increasing replacement of corn with hybrid rye

	Phase 1[1]				Phase 2[1]				Phase 3[1]			
Ingredient, %	0%	20%	40%	60%	0%	30%	60%	90%	0%	33%	66%	100%
Corn	39.96	31.98	23.97	15.97	53.40	37.41	21.43	5.45	60.27	40.29	20.33	-
Hybrid rye	-	8.00	16.00	24.00	-	16.00	32.00	48.00	-	20.00	40.00	60.34
Whey, dried	25.00	25.00	25.00	25.00	12.00	12.00	12.00	12.00	-	-	-	-
Soybean meal	20.00	20.00	20.00	20.00	24.50	24.50	24.50	24.50	35.00	35.00	35.00	35.00
Fish meal	8.00	8.00	8.00	8.00	6.00	6.00	6.00	6.00	-	-	-	-
Blood plasma	3.50	3.50	3.50	3.50	-	-	-	-	-	-	-	-
Soybean oil	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Limestone	0.76	0.74	0.74	0.74	0.87	0.90	0.94	0.99	0.86	0.91	0.97	1.01
Dicalcium phosphate	-	-	-	-	0.25	0.19	0.12	0.05	1.05	0.97	0.87	0.80
L-lysine HCl, 78%	0.21	0.20	0.20	0.20	0.34	0.34	0.33	0.32	0.25	0.24	0.23	0.22
DL-methionine, 98%	0.09	0.10	0.11	0.11	0.10	0.12	0.13	0.14	0.07	0.08	0.09	0.11
L-threonine, 98%	0.03	0.03	0.03	0.03	0.09	0.09	0.10	0.10	0.05	0.06	0.06	0.07

Table 6.1 (cont.)

	Phase 1[1]				Phase 2[1]				Phase 3[1]			
Ingredient, %	0%	20%	40%	60%	0%	30%	60%	90%	0%	33%	66%	100%
Salt	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Vitamin-mineral premix[2]	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]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 microminerals per kg of complete diet: Vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 as cholecalciferol, 2,208 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride,0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper sulfate and copper chloride; Fe, 126 mg as ferrous sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese sulfate; Se, 0.3 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc sulfate.

Table 6.2. Analyzed composition of diets with increasing replacement of corn with hybrid rye (as-is basis)

	Phase 1[1]				Phase 2[1]				Phase 3[1]			
Item	0%	20%	40%	60%	0%	30%	60%	90%	0%	33%	66%	100%
Dry matter, %	89.04	89.03	88.93	89.30	88.73	88.54	88.54	88.14	87.80	87.63	87.89	87.73
Ash, %	6.07	6.08	6.00	6.37	5.60	5.26	5.31	5.42	4.69	4.48	5.21	5.01
Gross energy, kcal/kg	3,972	4,022	4,039	4,007	4,005	4,020	3,988	3,984	4,016	3,998	3,978	3,962
ME[2], kcal/kg	3,460	3,441	3,421	3,402	3,409	3,371	3,333	3,295	3,367	3,319	3,272	3,223
Starch, %	20.45	20.67	19.79	19.80	28.85	29.66	26.18	25.25	34.80	31.20	33.09	25.24
Crude protein, %	22.88	22.94	23.66	23.48	21.67	22.07	21.61	22.18	20.90	21.97	22.06	23.00
IDF[3], %	8.90	8.40	9.10	9.20	9.40	10.20	11.50	11.70	11.40	13.70	13.90	14.60
SDF[3], %	0.90	1.40	2.10	2.80	0.80	2.10	1.70	2.60	1.10	1.40	1.60	3.10
TDF[3], %	9.80	9.80	11.20	12.00	10.20	12.20	13.20	14.30	12.50	15.00	15.40	17.70
AEE[3], %	4.46	4.36	4.11	4.04	4.68	4.51	4.22	4.21	4.67	4.00	3.81	2.76
Amino acids, %												
Arg	1.26	1.40	1.32	1.34	1.26	1.27	1.19	1.29	1.33	1.31	1.32	1.43
His	0.54	0.59	0.56	0.57	0.52	0.53	0.50	0.52	0.53	0.52	0.52	0.56
Ile	1.00	1.09	1.04	1.06	0.96	0.95	0.90	0.95	0.92	0.92	0.92	1.02

Table 6.2 (cont.)

	Phase 1[1]				Phase 2[1]				Phase 3[1]			
Item	0%	20%	40%	60%	0%	30%	60%	90%	0%	33%	66%	100%
Leu	1.87	2.03	1.88	1.87	1.74	1.67	1.54	1.58	1.70	1.64	1.56	1.65
Lys	1.59	1.74	1.66	1.68	1.53	1.53	1.45	1.50	1.36	1.32	1.31	1.42
Met	0.45	0.50	0.45	0.48	0.44	0.45	0.43	0.47	0.36	0.36	0.41	0.41
Cys	0.38	0.41	0.39	0.41	0.31	0.32	0.31	0.34	0.32	0.31	0.32	0.35
Phe	1.03	1.16	1.08	1.08	0.99	0.98	0.95	1.01	1.04	1.04	1.03	1.13
Thr	0.97	1.07	1.00	1.02	0.89	0.86	0.83	0.91	0.79	0.79	0.78	0.89
Trp	0.30	0.30	0.28	0.28	0.25	0.25	0.28	0.26	0.26	0.27	0.27	0.29
Val	1.16	1.30	1.22	1.23	1.02	1.03	0.98	1.04	0.98	1.00	1.00	1.11

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

[2]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).

[3]IDF = insoluble dietary fiber; SDF = soluble dietary fiber; TDF = total dietary fiber; AEE = acid-hydrolyzed ether extract.

Table 6.3. Growth performance of nursery pigs fed diets containing increasing concentrations of hybrid rye in a 3-phase feeding regimen during the initial 35 d post-weaning[1]

	Phase 3 corn replacement rate					*P* – values	
Item	0%	33%	66%	100%	SEM	Linear	Quadratic
Average body weight, kg							
Day 1	5.63	5.63	5.62	5.63	0.169	0.996	0.968
Day 7	5.86	6.17	6.09	6.26	0.180	0.179	0.706
Day 21	8.76	8.91	9.07	8.95	0.331	0.625	0.684
Day 35	16.73	16.46	16.93	16.07	0.520	0.521	0.566
Average daily gain, kg							
Phase 1, day 1 to 7	0.033	0.078	0.067	0.090	0.011	0.004	0.349
Phase 2, day 7 to 21	0.207	0.196	0.214	0.192	0.015	0.704	0.719
Phase 3, day 21 to 35	0.603	0.581	0.605	0.550	0.020	0.155	0.438
Overall, day 1 to 35	0.327	0.319	0.333	0.310	0.013	0.523	0.553
Average daily feed intake, kg							
Phase 1, day 1 to 7	0.085	0.119	0.115	0.128	0.009	0.004	0.256
Phase 2, day 7 to 21	0.314	0.295	0.317	0.347	0.020	0.193	0.240
Phase 3, day 21 to 35	0.814	0.777	0.828	0.925	0.042	0.050	0.121
Overall, day 1 to 35	0.487	0.466	0.496	0.551	0.024	0.047	0.120
Gain:feed							
Phase 1, day 1 to 7	0.277	0.650	0.566	0.703	0.086	0.004	0.179
Phase 2, day 7 to 21	0.669	0.661	0.666	0.559	0.024	0.006	0.042
Phase 3, day 21 to 35	0.748	0.747	0.734	0.607	0.023	<0.001	0.010
Overall, day 1 to 35	0.675	0.683	0.672	0.569	0.026	<0.001	0.002

[1]Least square means for dietary treatments represent 8 observations.

Table 6.4. Average fecal scores and incidence of diarrhea in pigs fed diets containing increasing concentrations of hybrid rye in a 3-phase feeding regimen during the initial 35 d post-weaning[1]

	Phase 3 corn replacement rate					*P* – values	
Item	0%	33%	66%	100%	SEM	Linear	Quadratic
Average fecal score[2]							
Phase 1, day 1 to 7	1.98	2.19	2.38	2.17	0.136	0.228	0.135
Phase 2, day 7 to 21	2.78	2.72	2.87	2.69	0.101	0.800	0.516
Phase 3, day 21 to 35	1.54	1.64	1.82	1.72	0.135	0.233	0.455
Overall, day 21 to 35	2.13	2.18	2.35	2.20	0.083	0.306	0.207
Diarrhea incidence[3], %							
Phase 1, day 1 to 7	25.00	33.33	37.50	29.17	9.882	0.693	0.386
Phase 2, day 7 to 21	51.79	55.36	57.14	48.21	6.677	0.768	0.357
Phase 3, day 21 to 35	0.00	10.71	3.57	8.29	4.133	0.971	0.972
Overall, day 1 to 35	25.74	33.09	31.62	28.68	4.035	0.663	0.199

[1]Least square means for dietary treatments represent 8 observations.

[2]Fecal scores: 1 = normal feces; 2 = moist feces; 3 = mild diarrhea; 4 = severe diarrhea; and 5 = watery diarrhea.

[3]Incidence of diarrhea calculated as number of days with fecal score ≥ 3 divided by total number of observation

Table 6.5. Complete blood count and serum analyses on day 21 post-weaning of pigs fed diets in which increasing proportions of corn were replaced with hybrid rye[1]

	Phase 3 corn replacement rate					*P* – values	
Item	0%	33%	66%	100%	SEM	Linear	Quadratic
Red blood cells, × 10^6 /μL	6.36	6.53	6.26	6.39	0.181	0.819	0.918
Hemoglobin, g/dL	10.20	10.35	10.25	9.85	0.267	0.344	0.312
Packed cell volume, %	33.24	33.71	33.36	32.19	0.848	0.363	0.339
Mean corpuscular volume, fl	52.40	51.90	53.68	50.46	1.552	0.565	0.390
Mean corpuscular hemoglobin, pg	16.11	15.93	16.50	15.46	0.529	0.566	0.429
Mean corpuscular hemoglobin concentration, g/dL	30.70	30.72	30.69	30.61	0.258	0.805	0.866
Platelets, × 10^5/μL	6.48	7.01	6.22	7.33	0.413	0.349	0.490
Total white blood cells[2], × 10^3/μL	21.78	25.71	25.43	24.04	1.800	0.426	0.151
Neutrophils, × 10^3/μL	10.69	12.17	13.98	13.52	1.172	0.060	0.416
Lymphocytes, × 10^3/μL	9.69	12.20	9.78	9.37	1.164	0.521	0.218
Monocytes, × 10^3/μL	0.85	0.65	1.11	0.78	0.115	0.614	0.521
Eosinophils, × 10^3/μL	0.25	0.57	0.25	0.14	0.107	0.196	0.056
Urea N, mg/dL	7.38	9.50	9.75	10.75	1.037	0.033	0.592

Table 6.5 (cont.)

	Phase 3 corn replacement rate					*P* – values	
Item	0%	33%	66%	100%	SEM	Linear	Quadratic
Albumin, g/dL	2.43	2.33	2.46	2.35	0.070	0.783	0.930
Total protein, g/dL	4.20	4.33	4.35	4.50	0.075	0.010	0.869

[1]Least square means for dietary treatments represent 8 observations.

[2]Band cells (or immature neutrophils) and basophils were quantified but not detected in most samples. Therefore, the data did not follow a normal distribution and were excluded from the table.

Table 6.6. Complete blood count and serum analyses on day 35 post-weaning of pigs fed diets in which increasing proportions of corn were replaced with hybrid rye[1]

	Phase 3 corn replacement rate					*P* – values	
Item	0%	25%	50%	75%	SEM	Linear	Quadratic
Red blood cells, × 10^6 /μL	6.65	6.50	6.54	6.70	0.170	0.790	0.359
Hemoglobin, g/dL	11.95	11.51	12.00	11.63	0.239	0.631	0.897
Packed cell volume, %	38.26	36.17	38.14	37.44	0.797	0.882	0.377
Mean corpuscular volume, fl	57.68	55.79	58.57	55.91	1.275	0.645	0.758
Mean corpuscular hemoglobin, pg	18.03	17.79	18.41	17.36	0.414	0.443	0.320
Mean corpuscular hemoglobin concentration, g/dL	31.24	31.86	31.44	31.08	0.217	0.333	0.027
Platelets, × 10^5/μL	5.43	5.09	5.94	5.79	0.448	0.317	0.831
Total white blood cells[2], × 10^3/μL	12.79	13.40	16.00	15.83	1.618	0.118	0.813
Neutrophils, × 10^3/μL	4.32	3.53	4.24	6.18	0.810	0.077	0.095
Lymphocytes, × 10^3/μL	7.36	9.02	11.05	8.69	1.072	0.208	0.068
Monocytes, × 10^3/μL	0.70	0.60	0.64	1.07	0.213	0.225	0.219
Eosinophils, × 10^3/μL	0.17	0.20	0.06	0.13	0.051	0.226	0.654
Urea N, mg/dL	10.75	12.75	11.88	13.63	0.731	0.025	0.866

Table 6.6 (cont.)

	Phase 3 corn replacement rate					*P* – values	
Item	0%	25%	50%	75%	SEM	Linear	Quadratic
Albumin, g/dL	2.84	2.71	2.86	2.83	0.084	0.767	0.607
Total protein, g/dL	4.76	4.70	4.76	4.89	0.091	0.290	0.311

[1]Least square means for dietary treatments represent 8 observations.

[2]Band cells (or immature neutrophils) and basophils were quantified but not detected in most samples. Therefore, the data did not follow a normal distribution and were excluded from the table.

Table 6.7. Serum analyses for cytokines and inflammatory markers on day 21 and day 35 post-weaning of pigs fed diets in which increasing proportions of corn were replaced with hybrid rye [1]

	Phase 3 corn replacement rate					*P* – values	
Item	0%	33%	66%	100%	SEM	Linear	Quadratic
Day 21, pg/mL							
IL[2]-1α	7.8	4.8	8.2	16.6	5.26	0.267	0.310
IL-1β	68.6	45.1	86.7	143.0	26.42	0.047	0.146
IL-1RA[2]	266.5	293.8	272.0	407.4	48.21	0.097	0.333
IL-2	134.5	47.0	77.8	148.5	41.98	0.664	0.050
IL-4	166.5	74.4	92.4	225.9	71.27	0.624	0.107
IL-6	24.1	9.5	17.0	28.3	10.89	0.672	0.204
IL-8	254.0	326.6	487.0	378.7	84.67	0.138	0.292
IL-10	318.0	137.7	161.0	287.7	63.88	0.910	0.018
IL-12	818.7	929.0	991.1	991.1	87.34	0.139	0.506
IL-18	674.4	548.3	600.8	855.8	111.09	0.286	0.102
IFN-γ[2]	1,775.6	1,474.0	1,422.7	1,168.0	622.82	0.512	0.990
TNF-α[2]	43.0	25.6	49.0	56.4	10.47	0.172	0.182
IgG[2], mg/mL	3.12	3.90	3.77	5.09	0.831	0.132	0.749
Day 35, pg/mL							
IL-1α	4.1	10.5	9.0	11.5	6.06	0.263	0.560
IL-1β	52.0	86.7	62.5	71.0	31.66	0.709	0.605
IL-1RA	295.9	544.1	278.6	238.8	65.03	0.137	0.056

Table 6.7 (cont.)

	Phase 3 corn replacement rate					*P* – values	
Item	0%	33%	66%	100%	SEM	Linear	Quadratic
Day 35, pg/mL							
IL-2	53.9	73.1	36.2	67.1	36.58	0.985	0.769
IL-4	86.3	134.6	70.6	88.1	71.66	0.823	0.849
IL-6	13.8	33.4	21.9	40.3	16.74	0.183	0.774
IL-8	278.1	657.2	632.7	490.7	94.91	0.054	0.006
IL-10	212.8	226.4	131.7	165.7	76.06	0.395	0.807
IL-12	977.2	1,082.9	1,095.8	797.3	93.12	0.161	0.034
IL-18	504.9	609.5	473.3	562.3	132.27	0.934	0.968
IFN-γ	2,323.3	226.0	635.8	1,075.6	580.65	0.457	0.002
TNF-α	51.8	35.4	47.8	33.7	16.77	0.441	0.956
IgG, mg/mL	1.82	1.74	2.64	2.23	0.470	0.317	0.735

[1]Least square means for dietary treatments represent 8 observations.

[2]IL = interleukin; IL-1RA = IL-1 receptor antagonist; IFNγ = interferon-gamma; TNF-α = tumor necrosis factor-α; IgG = Immunoglobulin G.

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CHAPTER 7: Preference for feed, but not growth performance, is reduced if hybrid rye replaces corn in diets for growing pigs

Abstract

Two experiments were conducted to test the hypotheses that there is no difference in feed preference for diets containing hybrid rye or corn as the exclusive cereal grain source, and that hybrid rye may replace a portion of corn in diets for growing pigs without adversely affecting growth performance. In experiment 1, 36 pigs (initial body weight 32.0 ± 1.8 kg) were housed for 8 d in 18 pens with one gilt and one barrow in each pen. Each pen contained 2 identical feeders with one feeder containing a corn-based diet and the other feeder containing a diet based on hybrid rye. Each day, feed disappearance was calculated, feed allotment was recorded, and feeder positions were switched to minimize feeder preference. In experiment 2, 128 growing pigs (initial body weight 27.2 ± 2.2 kg) were allotted to 32 pens and 4 dietary treatments. A diet identical to the corn diet used in experiment 1 was used as the control diet, and 3 additional diets in which increasing proportions of corn were replaced with hybrid rye, were also formulated. Diets were fed for 27 d and body weights were determined at the start and at the end of the experiment. Results of experiment 1 demonstrated that preference (%) for the hybrid rye-based diet was less ($P < 0.05$) than for the corn-based diet on each day and for the overall experiment. Results of experiment 2 indicated that there were no differences among treatments for initial or final body weight of pigs. Average daily gain (ADG) was not affected by dietary treatment, and the same was true for gain:feed (G:F). There was a tendency (linear, $P < 0.10$) for average daily feed intake to be reduced as hybrid rye inclusion in the diet increased. The reluctance of pigs to consume hybrid rye in the first experiment may be due to simple taste preference, but the

satiating effects of the dietary fiber in hybrid rye in the gastrointestinal tract may also have contributed to the reduced feed intake observed in the second experiment. Nevertheless, ADG and G:F were unchanged by hybrid rye substitution for corn, indicating that growing pigs may be fed diets with high inclusion rates of hybrid rye without negatively impacting growth.

Key words: corn, feed preference, growing pigs, growth performance, hybrid rye

Abbreviations

ADG	average daily gain
ADFI	average daily feed intake
DDGS	distillers dried grains with solubles
G:F	gain:feed

Introduction

Varieties of hybrid rye originally developed in Europe are superior to older cultivars of rye because they have greater grain yield, better uniformity, and greater lodging resistance (Geiger and Miedaner, 2009). Hybrid rye's ability to withstand drought, poor soil quality, or extreme cold better than other crops makes it an alternative to growing corn or small grains (Geiger and Miedaner, 2009). Results of research from Europe and Canada have demonstrated that replacing barley with hybrid rye in diets for growing and finishing pigs does not reduce animal growth performance (Schwarz et al., 2015; 2016; Bussières, 2018), but substituting hybrid rye for wheat reduced average daily gain (**ADG**) and average daily feed intake (**ADFI**) in finishing pigs (Smit et al., 2019). In many parts of the world, including the United States, corn is the primary energy source in diets for pigs, but there are no published data comparing growth performance of growing pigs fed diets in which hybrid rye replaces corn. Unfamiliarity with hybrid rye also makes some producers in the United States reluctant to feed hybrid rye to pigs, as there is a long-standing belief that rye is less palatable to other livestock species than other feed ingredients (e.g., Brooks, 1911; Halpin et al., 1936; Sharma et al., 1981). Taste preference of weanling pigs for rye has been compared against a reference diet containing white rice, and subsequently compared with other cereal grains, including corn (Solà-Oriol et al., 2009a; 2009b). However, because no data directly comparing the preference of growing pigs for consuming hybrid rye versus corn have been published, 2 experiments were conducted to test the hypotheses that there is no difference in feed preference for diets containing hybrid rye or corn, and that hybrid rye may replace a portion of corn in diets for growing pigs without adversely affecting growth. Because hybrid rye contains approximately 94% of the metabolizable energy compared with corn (McGhee and Stein, 2020a), and pigs generally consume feed to meet their energy requirement (Patience, 2012), it was also hypothesized that growing pigs fed hybrid rye will consume more feed compared with pigs fed corn to compensate for the reduced metabolizable energy in hybrid rye.

Materials and Methods

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

Animals, housing, experimental design

Experiment 1

Eighteen gilts and 18 barrows with an initial body weight of 32.0 ± 1.8 kg were used in the experiment. One barrow and one gilt were housed in each pen; therefore, there were 18 replicate pens in the experiment. All pens had slatted floors, 2 nipple waterers, and 2 identical stainless-steel feeders. One diet based on corn and soybean meal, and one diet based on hybrid rye and soybean meal, were formulated to meet or exceed the estimated nutrient requirements for 25 to 50 kg pigs (NRC, 2012; Table 7.1). Diets were formulated based on published values for metabolizable energy, standardized ileal digestible amino acids, and standardized total tract digestible P in hybrid rye (McGhee and Stein, 2018; 2019; 2020a) and corn and soybean meal (NRC, 2012). The same source of hybrid rye as used in chapter 3 was used in the present experiments. All pigs were allowed *ad libitum* access to the corn-soybean meal diet in one feeder and the hybrid rye-soybean meal diet in the second feeder. The positions of the 2 feeders were switched daily to minimize the effect of feeder location preference. Feed allotment and disappearance were recorded daily during the 8 d experiment.

Experiment 2

A total of 128 growing pigs with an initial body weight of 27.2 ± 2.2 kg were allotted to a completely randomized design with 4 treatment groups. Sex was balanced within pen. Thirty-two pens were used with 4 pigs per pen and 8 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. Water and feed were available to the pigs on an *ad libitum* basis.

Pigs were fed experimental diets for 27 d, and all diets were fed in mash form. A control diet primarily based on corn and soybean meal was formulated (Table 7.2). Three additional diets were formulated by replacing 33, 66, or 100% of the corn in the control diet with hybrid rye. All diets were formulated to meet or exceed the estimated requirements for standardized ileal digestible amino acids, vitamins, and minerals for 25 to 50 kg pigs (NRC, 2012). Diets were formulated based on published values for metabolizable energy, standardized ileal digestible amino acids, and standardized total tract digestible P in hybrid rye (McGhee and Stein, 2018; 2019; 2020a) and corn and soybean meal (NRC, 2012). Diets were not formulated to be isocaloric or isonitrogenous; therefore, as hybrid rye inclusion rate increased, the calculated concentration of total dietary fiber and crude protein increased, whereas the calculated concentration of metabolizable energy decreased. Individual pig weights were obtained at the beginning and at the conclusion of the experiment. Feed allowance was recorded daily, and feed left in the feeders at the conclusion of the experiment was weighed to calculate feed disappearance.

Chemical analyses

Samples of diets from both experiments were analyzed for dry matter by oven drying at 135 °C for 2 h (method 930.15; AOAC Int., 2007). These samples were also analyzed for ash (method 942.05; AOAC Int., 2007). Nitrogen was measured (method 990.03; AOAC Int., 2007) using a Leco Nitrogen Determinator (model FP628, Leco Corp., St. Joseph, MI, USA) and crude 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. Starch was analyzed by the glucoamylase procedure (method 979.10; AOAC Int., 2007), which yields the enzymatically hydrolyzed starch in the sample. The gross energy in diets were measured using an isoperibol bomb calorimeter (model 6400, Parr

Instruments, Moline, IL, USA) with benzoic acid used as the standard for calibration, and the 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 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. 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].

Calculations and statistical analysis

Experiment 1

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

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

Data were analyzed using SAS 9.4 (SAS Institute Inc., Cary, NC). Pen was the experimental unit. Normality of residuals was confirmed using the UNIVARIATE procedure. Data were analyzed by the paired *t*-test in SAS. Results were considered significant at $P \leq 0.05$.

Experiment 2

Pen was considered the experimental unit, and data were summarized for each treatment group. Average daily gain, ADFI, and G:F were calculated. 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, but none were identified in the data set. Data were analyzed by the MIXED procedure, and the statistical model included the fixed effect of diet and the random effect of pen. 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. Results were considered significant at $P \leq 0.05$ and considered a trend at $0.05 < P \leq 0.10$.

Results and Discussion

In experiment 1, pigs consumed more ($P < 0.05$) of the corn-based diet than of the rye-based diet from day 1 through day 8, and for the overall period (Table 7.3). Subsequently, the calculated preference (%) for the hybrid-rye based diet was less ($P < 0.05$) than for the corn-based diet for each day and for the overall period. The very strong preference for corn versus rye indicates that the historical reluctance to feed rye due to poor palatability has merit. However, results of research conducted with pigs naïve to test ingredients demonstrated that weanling pigs' preference for rye or corn did not differ when fed at 30, 60, or 100% inclusion rates (Solà-Oriol et al., 2009a). Reduced preference for corn compared with rye was also observed at 50% inclusion of cereal grains (Solà-Oriol et al., 2009b). It is possible the different age of pigs used in this experiment may explain some of the discrepancies between data from the present experiment and the data by Solà-Oriol et al. (2009a; 2009b) because although young pigs often exhibit reluctance to consume feed immediately after weaning, preference toward particular ingredients is generally more pronounced as pigs get older (Seabolt et al., 2010). The pigs used in the present experiment were familiar with diets containing corn and had never been exposed to hybrid rye prior to the experiment, which may partially explain why pigs strongly preferred corn to rye. Neophobia may be a confounding factor to evaluating preference for feed (Solà-Oriol et al., 2011), and a pig's prior experience with a particular ingredient may affect how quickly they adapt to consuming a new bulkier diet (Tsaras et al., 1998). However, an animal's previous experience consuming an ingredient has minimal impact on feed preference after 1 or 2 d, at which point the sensory characteristics (i.e., taste and smell) of the ingredient dictate feed preference more than familiarity with the ingredient (Solà-Oriol et al., 2009b; Seabolt et al., 2010). Furthermore, increased exposure (i.e., inclusion rate and duration) to a low-palatable diet resulted in a linear reduction in preference, rather than an increased tolerance, in two-way choice experiments (Seabolt et al., 2010; Solà-Oriol et al., 2011). It is possible that maternal experience with dietary ingredients and flavors have lasting impact on the flavor preferences of pigs (Figueroa et al., 2013). As a consequence, pigs used in the present experiment may have been predisposed to preferring corn instead of a novel ingredient such as hybrid rye as these pigs were the offspring of sows fed diets traditional for the United States consisting of corn and soybean meal. In contrast, much research demonstrating a low preference for corn by weanling pigs was conducted in Europe, where the usage of cereal grains other than corn in diets for pigs is more common.

If previous exposure to an ingredient cannot fully explain the feeding preferences of pigs, the physical and chemical characteristics of hybrid rye compared with corn must be considered. Solà-Oriol et al. (2013) demonstrated a positive correlation between digestible starch and feed preference, as well as a negative correlation between crude fiber and feed preference. Corn contains more digestible starch than hybrid rye (McGhee and Stein, 2018; 2020a), which may contribute to the increased preference for corn observed in the present experiment. Hybrid rye contains more dietary fiber than corn (McGhee and Stein et al., 2018; 2020a), and dietary fiber impacts the bulkiness of the diet, the amount of water consumed during and after eating, the energy spent chewing, and the viscosity and transit time of the digesta in the gastrointestinal tract (Kyriazakis and Emmans, 1995; Tsaras et al., 1998; Whittemore et al., 2001; Solà-Oriol et al., 2009a). Soluble arabinoxylans in rye may increase intestinal digesta viscosity more than other cereal grains containing less soluble fiber (Thacker et al., 1999; Bartelt et al., 2002; Bach Knudsen et al., 2005; Le Gall et al., 2009; 2010), and a correlation exists between ileal digesta viscosity and feed preference of cereal grains (Solà-Oriol et al., 2007). The mechanism of digesta viscosity impacting feed intake in humans may be related to fiber swelling and binding of water in the gastrointestinal tract, followed by gastric distension and slow digesta passage rate (Kristensen and Jensen, 2011). The viscous nature of the digesta may also reduce digestive enzyme efficiency, delay or block nutrient absorption, and result in reduced nutrient digestibility and subsequent activation of the ileal brake (Kristensen and Jensen, 2011; van Avesaat et al., 2015). The slow passage rate of digesta from the stomach and from the ileum may also increase satiety signaling to the brain, thereby reducing feed intake (Kristensen and Jensen, 2011).

Hybrid rye's flavor profile differs from corn as well, which likely also influences feed preference. Several volatile compounds in the fibrous outer pericarp of rye may contribute to the reduced palatability of rye compared with corn, as they are perceived as tasting bitter (Grosch and Schieberle, 1997; Heiniö et al., 2003; Poutanen et al., 2014). The texture of a diet also impacts preference – increased hardness and fragility of an ingredient is negatively correlated with preference (Solà-Oriol et al., 2007). Rye, if ground too finely or with too low moisture content, gets pulverized and increases the dustiness of the diet (Bazylo, 1992).

Pigs prefer diets containing corn and soybean meal to diets containing corn, soybean meal, and distillers dried grains with solubles (**DDGS**), and one main explanation for the reduced preference for DDGS is its greater concentration of dietary fiber (Seabolt et al., 2010; Kim et al., 2012). Although pigs strongly prefer diets without DDGS when given the choice, feed intake is not compromised when a single diet consisting of corn, soybean meal, and DDGS is provided (Kim et al., 2012). Therefore, even though pigs demonstrated strong preference for corn over hybrid rye in experiment 1, it was hypothesized in experiment 2 that when pigs were offered a single diet, feed intake would be greater as inclusion of hybrid rye in the diets increased due to the reduced metabolizable energy in hybrid rye compared with corn. However, the hypothesis was not supported, as there was a tendency (linear, $P < 0.10$) for ADFI to be reduced as hybrid rye inclusion in the diet increased (Table 7.4). The reduction in ADFI at high inclusion rates of hybrid rye may be a reflection of the preference for corn observed in experiment 1, in combination with greater gut fill and satiation.

In experiment 2, no differences were observed among treatments for initial or final body weight. Average daily gain was not affected by dietary treatment, and the same was true for G:F, despite the reduced calculated metabolizable energy in diets containing hybrid rye. Results of recently conducted research in gestating sows also demonstrated no difference in ADG when graded levels of hybrid rye were fed at the expense of corn, despite reduced estimations for the metabolizable energy in diets containing hybrid rye (McGhee and Stein, 2020a; 2020b). Thus, it is possible the experimentally determined metabolizable energy values for hybrid rye compared with corn are underestimated (McGhee and Stein, 2020a).

Results of research comparing the growth performance of growing-finishing pigs fed hybrid rye as a replacement for barley indicate hybrid rye results in either no differences or slight improvements in ADG, ADFI, G:F, and carcass characteristics (Schwarz et al., 2015; Bussières, 2018). In contrast, when hybrid rye replaces wheat in diets for growing-finishing pigs, a depression in ADG and ADFI is observed as the inclusion of hybrid rye in the diet increases (Smit et al., 2019). The reduced growth performance observed when hybrid rye replaces wheat at large inclusion rates is likely due to hybrid rye's greater proportion of dietary fiber, reduced starch, and consequently reduced metabolizable energy compared with wheat (McGhee and Stein, 2020a). The opposite is true for barley – hybrid rye contains less dietary fiber, more starch, and more metabolizable energy than barley, and feeding hybrid rye results in similar or better growth performance in growing-finishing pigs. Although no differences were observed for ADG or G:F in the present 27-d experiment, more research is needed to determine if growth performance and carcass quality of growing-finishing pigs will be reduced when hybrid rye replaces corn at high inclusion rates and during the entire grow-finish period.

Conclusions

Pigs strongly preferred a diet containing corn as the exclusive cereal grain compared with a diet based on hybrid rye when given a choice. When pigs were provided with a single diet, ADFI also tended to be reduced as the inclusion of hybrid rye in the diet increased. Despite reduced ADFI, the ADG, G:F, and final body weights did not differ among dietary treatments. More research is warranted to test the effects of feeding hybrid rye to pigs for a longer duration than the 27 d used in the present experiment.

Tables

Table 7.1. Composition of diets in experiment 1 (as-is basis)

Item	Corn	Hybrid rye
Ingredient, %		
Hybrid rye	-	67.45
Corn	67.38	-
Soybean meal	27.00	27.00
Soybean oil	3.00	3.00
Ground limestone	0.85	0.99
Dicalcium phosphate	1.00	0.77
L-lysine HCl, 78%	0.18	0.15
DL-methionine, 98%	0.02	0.05
L-threonine, 98%	0.02	0.04
Sodium chloride	0.40	0.40
Vitamin-mineral premix[1]	0.15	0.15
Analyzed composition		
Dry matter, %	87.51	87.77
Ash, %	4.49	4.30
Gross energy, kcal/kg	4,004	3,981
Metabolizable energy[2], kcal/kg	3,429	3,267
Starch, %	42.38	32.63
Insoluble dietary fiber, %	11.00	15.80
Soluble dietary fiber, %	1.30	3.40

Table 7.1 (cont.)

Item	Corn	Hybrid rye
Total dietary fiber, %	12.30	19.20
Acid-hydrolyzed ether extract, %	5.77	4.35
Crude protein, %	17.72	19.05
Arg, %	1.20	1.16
His, %	0.48	0.45
Ile, %	0.83	0.79
Leu, %	1.62	1.34
Lys, %	1.13	1.13
Met, %	0.27	0.30
Cys, %	0.28	0.31
Phe, %	0.97	0.94
Thr, %	0.72	0.71
Trp, %	0.22	0.23
Val, %	0.87	0.87

[1]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;

Table 7.1 (cont.)

Mn, 60.2 mg as manganese hydroxychloride; Se, 0.30mg as sodium selenite and selenium yeast; and Zn, 125.1mg as zinc hydroxychloride.

[2]Metabolizable energy was calculated rather than analyzed and based on the value 3,150 kcal/kg metabolizable energy in hybrid rye (McGhee and Stein, 2020a), and values for all other ingredients according to NRC (2012).

Table 7.2. Composition of diets in experiment 2 (as-is basis) in which 0, 33, 66, or 100% of corn from a corn-soybean meal control diet was replaced with hybrid rye[1]

Item	0%	33%	66%	100%
Ingredient, %				
Corn	67.37	45.14	22.25	-
Hybrid rye	-	22.24	45.16	67.45
Soybean meal	27.00	27.00	27.00	27.00
Soybean oil	3.00	3.00	3.00	3.00
Limestone	0.85	0.89	0.94	0.99
Dicalcium phosphate	1.00	0.94	0.86	0.77
L-lysine HCl, 78%	0.19	0.18	0.17	0.15
DL-methionine, 98%	0.02	0.03	0.04	0.05
L-threonine, 98%	0.02	0.03	0.03	0.04
Salt	0.40	0.40	0.40	0.40
Vitamin-mineral premix[2]	0.15	0.15	0.15	0.15
Analyzed composition				
Dry matter, %	87.72	87.14	87.89	87.88
Ash, %	4.42	4.49	4.68	4.79
Gross energy, kcal/kg	3,989	3,972	3,962	3,972
Metabolizable energy[3], kcal/kg	3,429	3,374	3,319	3,267
Starch, %	37.43	39.56	37.36	36.39
Insoluble dietary fiber, %	12.10	13.40	15.80	15.50
Soluble dietary fiber, %	1.00	1.00	2.10	4.60

Table 7.2 (cont.)

Item	0%	33%	66%	100%
Total dietary fiber, %	13.10	14.40	17.90	20.00
Acid-hydrolyzed ether extract, %	6.01	5.42	4.71	4.65
Crude protein, %	16.90	17.60	19.06	19.14
Arg, %	1.22	1.16	1.19	1.20
His, %	0.48	0.48	0.48	0.48
Ile, %	0.88	0.82	0.84	0.84
Leu, %	1.63	1.51	1.48	1.38
Lys, %	1.19	1.20	1.17	1.15
Met, %	0.28	0.30	0.32	0.34
Cys, %	0.30	0.32	0.33	0.35
Phe, %	0.97	0.93	0.96	0.96
Thr, %	0.71	0.71	0.74	0.78
Trp, %	0.22	0.24	0.22	0.23
Val, %	0.93	0.88	0.91	0.92

[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 microminerals per kg of complete diet: Vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 as cholecalciferol, 2,208 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride,0.24 mg; vitamin B_{12}, 0.03 mg; D-

Table 7.2 (cont.)

pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper sulfate and copper chloride; Fe, 126 mg as ferrous sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese sulfate; Se, 0.3 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc sulfate.

[3]Metabolizable energy was calculated rather than analyzed and based on the value 3,150 kcal/kg metabolizable energy in hybrid rye (McGhee and Stein, 2020a), and values for all other ingredients according to NRC (2012).

Table 7.3. Daily and overall feed disappearance and feed preference, experiment 1[1]

Item	Corn	Hybrid rye	SD	*P*-value
Feed disappearance, kg				
Day 1	1.94 ± 0.69	0.24 ± 0.16	-	<0.001
Day 2	1.44 ± 0.53	0.87 ± 0.44	-	0.027
Day 3	2.71 ± 0.54	0.24 ± 0.10	-	<0.001
Day 4	1.97 ± 0.56	0.69 ± 0.47	-	<0.001
Day 5	3.12 ± 0.56	0.29 ± 0.37	-	<0.001
Day 6	2.82 ± 0.86	0.49 ± 0.36	-	<0.001
Day 7	2.93 ± 0.17	0.35 ± 0.33	-	<0.001
Day 8	3.26 ± 0.82	0.91 ± 1.88	-	<0.001
Overall	20.21 ± 8.21	4.07 ± 5.40	-	<0.001
Feed preference, %				
Day 1	85.9	14.1	26.92	<0.001
Day 2	61.8	38.2	25.04	0.031
Day 3	90.7	9.3	14.98	<0.001
Day 4	74.0	26.0	22.93	<0.001
Day 5	91.9	8.1	17.00	<0.001
Day 6	86.0	14.0	14.66	<0.001
Day 7	90.9	9.1	11.19	<0.001
Day 8	81.3	18.7	24.04	<0.001
Overall	83.4	16.6	9.55	<0.001

[1]Means for dietary treatments represent 18 observations.

Table 7.4. Growth performance of pigs fed diets in which portions of corn in a corn-soybean meal control diet were replaced with hybrid rye, experiment 2[1]

	Corn replacement rate					*P* – values	
Item	0%	33%	66%	100%	SEM	Linear	Quadratic
Body weight, day 1, kg	27.14	27.19	27.12	27.18	0.797	0.993	0.995
Body weight, day 27, kg	52.46	53.83	52.18	51.98	1.138	0.547	0.495
Average daily gain, kg	0.938	0.988	0.926	0.918	0.022	0.228	0.192
Average daily feed intake, kg	1.841	1.905	1.783	1.766	0.041	0.068	0.338
Gain:feed	0.510	0.518	0.522	0.521	0.009	0.388	0.609

[1]Least square means for dietary treatments represent 8 observations.

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CHAPTER 8: Hybrid rye may replace corn in diets for growing-finishing pigs without influencing most carcass traits, but feed intake may be reduced at high inclusion rates, thus limiting growth rate potential

Abstract

An experiment was conducted to test the hypothesis that hybrid rye may replace a portion of or all 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 4 treatments with 8 replicate pens per treatment. Phase 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 either a control diet based on corn and soybean meal, or a diet in which 33, 66, or 100% of the corn in the control diet was replaced with hybrid rye. One pig per pen was harvested at the conclusion of the experiment. With increased hybrid rye inclusion in the diet, average daily gain (ADG) and average daily feed intake (ADFI) decreased in phase 1 (linear, $P < 0.05$). In phase 3, gain:feed (G:F) increased and then was reduced (quadratic, $P < 0.05$) with greater hybrid rye inclusion in the diet. However, overall ADG, ADFI, and G:F for the 97-d period were not different among treatments. Most measured carcass characteristics were not influenced by diet, but loin visual color score decreased (linear, $P < 0.05$) and backfat instrumental color was lighter (linear, $P < 0.05$) with greater amounts of hybrid rye in the diet. Weights of heart, kidney, liver, and the empty gastrointestinal tract increased (linear, $P < 0.05$) with increased hybrid rye in the diet. In conclusion, pigs consumed less feed in the first phase of the experiment as dietary hybrid rye

increased, which resulted in reduced ADG, but overall growth performance traits did not differ among treatments. Results of the present experiment indicate that hybrid rye may replace up to 100% of 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, cereal grains, corn, growing pigs, finishing pigs, hybrid rye

Abbreviations

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

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 et al., 2018). Hybrid rye may also substitute wheat in diets for growing pigs 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). Results from research recently conducted at the University of Illinois indicate that 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. Furthermore, in a two-way choice preference test, pigs strongly 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, no published data exist for effects of feeding hybrid rye in place of corn over the duration of growing and finishing phases, and no data for carcass characteristics of pigs fed hybrid rye instead of corn have been published. Therefore, an experiment was conducted to test the hypothesis that ADG and carcass characteristics will not differ when hybrid rye partially replaces corn in diets for growing-finishing pigs, but it was also hypothesized that reduced ADFI will be observed if hybrid rye replaces 100% of the corn in diets for growing and finishing pigs.

Materials and Methods

The experiment was conducted at the Swine Research Center at the University of Illinois following a protocol approved by the Institutional Animal Care and Use Committee at the University of Illinois. 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 4 treatment groups. Sex was balanced within pen across treatments. Thirty-two pens were used with 4 pigs per pen and 8 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. Water and feed were available to the pigs on an *ad libitum* basis. All diets were fed in mash form.

Diets were fed in 3 phases with phase 1 grower diets being fed for 35 d, phase 2 early finisher diets for 35 d, and phase 3 late finisher diets for 27 d. 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 8.1). The hybrid rye used in the present experiment was sourced from a feed mill in Lexington, KY, USA and was grown in 2020. 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 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 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 was recorded.

At the conclusion of phase 3, the pig in each pen with the body weight closest to the pen mean was harvested at the Meat Science Laboratory at the University of Illinois. Within each treatment, 4 gilts and 4 barrows were harvested. Immediately prior to slaughter, pigs were weighed to determine end 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 weights of liver, kidney, heart, and full and empty gastrointestinal tracts were also recorded. Carcasses were split down the midline and stored 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 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 following the procedure established by the National Pork Producers Council (National Pork Producers Council, 1999). Ultimate pH 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). Subjective color and marbling scores (National Pork Producers Council, 1999) and firmness scores (National Pork Producers Council, 1991) were determined by a single technician. The loin eye area was measured in duplicate by tracing the surface of the longissimus muscle on a double-matted acetate paper, and the average of the 2 measurements was recorded. Drip loss was measured according to Boler et al. (2011). Carcass yield (%) was calculated by dividing hot carcass weight by end live weight and multiplied by 100. Fat free lean (%) was calculated using the following equation: [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-Bratler 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 then weighed. Loin chops were cooked on open hearth grills and considered done at 63 or 71 °C, at which point they were allowed to cool to room temperature, and final weight was measured. Cook loss was expressed as a percentage and calculated by subtracting cooked weight from initial weight and dividing by initial weight. Warner-Bratzler shear force was measured in 4 cores (1.25 cm diameter) per chop 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 s and a load cell capacity of 100 kg. The mean shear force of the 4 cores for each loin chop was reported. Sensory characteristics were evaluated by 6 independent 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 of diet samples from each batch were mixed within diet and phase, and a subsample of the mixed samples were finely ground with a coffee bean grinder and analyzed. Diet samples and a sample of hybrid rye were analyzed for dry matter (method 930.15; AOAC Int., 2007) and for 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 3*N* HCl (Ankom^{HCl}, Ankom Technology, Macedon, NY, USA). 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. 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]. 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. Average daily gain, 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 was 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 considered the experimental unit. Normality of residuals were 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) were identified and removed: hot carcass weight (control), heart weight (25% replacement), ultimate loin pH (control), loin b* (100% replacement), backfat b* (75% replacement), and full and empty gastrointestinal weight (control). Data were analyzed by the MIXED procedure, and the statistical model included the fixed effect of diet and random effect of replicate. End live weight was also included 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 8.2). The hybrid rye used in the experiment contained 1.69 mg/kg ergot alkaloids. On day 35, 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 8.3). Average daily gain was linearly decreased ($P < 0.05$) as hybrid rye inclusion in the grower diet increased, but ADG did not differ 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 overall 97-d period, ADG did not differ among treatments. Average daily feed intake 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 live body 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 8.4). Loin visual color score decreased (linear, $P < 0.05$) with hybrid rye inclusion, but loin visual marbling, subjective firmness, instrumental color, cook loss, and shear force did not differ among treatments. Backfat color was lighter (linear, $P < 0.05$) with greater amounts of rye in the diet, but backfat redness and yellowness were not different among treatments. Organ weights, including heart, kidney, liver, and empty gastrointestinal tracts were heavier (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. Hybrid rye yields more t per hectare than open-pollinated rye, and it can also outyield other small grains when managed correctly (Geiger and Miedaner, 1999, Jørgensen et al., 2007; Geiger and Miedaner, 2009; Hübner et al., 2013; Schittenhelm et al., 2013; Laidig et al., 2017). Compared with corn and small grains like 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 hybrids of rye are less susceptible to ergot contamination and have reduced presence of antinutritional factors compared with conventional open-pollinated rye (Makarska et al., 2007, cited by Schwarz et al., 2015; Miedaner and Geiger, 2015) and is a viable alternative feedstuff for livestock diets.

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). As determined in growing pigs, the metabolizable energy in hybrid rye 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).

Several experiments have been conducted to test the hypothesis that hybrid rye may replace barley or wheat in diets for growing-finishing pigs without influencing growth performance. In two experiments conducted in Poland, finishing pigs fed hybrid rye in place of barley had greater ADG and ADFI (Schwarz et al., 2015; 2016). Similarly, overall ADG, ADFI, and G:F were not different when portions of wheat and barley were substituted with hybrid rye at inclusion rates up to 20 and 50% in early growing and late finishing phase diets, respectively (Bussières, 2018). However, ADFI was reduced when pigs were fed diets in which hybrid rye replaced portions of wheat, and this observation 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. To date, no peer-reviewed data exist for the growth performance of growing-finishing pigs fed increasing concentrations of hybrid rye at the expense of corn.

Previous research conducted at the University of Illinois indicate growing pigs strongly prefer diets containing corn to diets containing hybrid rye when given the choice (McGhee and Stein, 2021). The pigs used in the experiment may have been predisposed to preferring corn due to their experience of being fed corn prior to the experiment, but the flavor profile of hybrid rye may have also contributed toward the pigs' reluctance to consume the diet containing hybrid rye. Rye contains more volatile compounds perceived as tasting bitter (Grosch and Schieberle, 1997; Heiniö et al., 2003; Poutanen et al., 2014; Katina et al., 2014); thus, one reason ADFI decreased in the first phase of the experiment as hybrid rye inclusion in the diet increased may be because of the inexperience of pigs with the flavor of the new ingredient. It is hypothesized that if pigs are adapted to consuming hybrid rye in nursery diets, ADFI will not be reduced when hybrid rye is included in grower diets, but this has not been experimentally tested.

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; Bartelt et al., 2002; 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, likely speeding up gut fill of pigs (Avelar et al., 2011; Ndou et al., 2013; De Jong et al., 2014). Thus, 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).

Although ADG was reduced in the grower phase, pigs compensated in later phases. Hybrid rye contains less metabolizable energy than corn when fed to 28 kg pigs (McGhee and Stein, 2020), but results of the present experiment indicate that hybrid rye is well utilized by finishing pigs as G:F would be expected to be reduced if a lower-energy feedstuff was fed. Weights of gastrointestinal tracts were greater from pigs fed hybrid rye, suggesting greater 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 as fermentative capacity increases with age (Le Goff et al., 2002). A more speculative hypothesis for the increased G:F observed in the finishing pigs fed hybrid rye in the present experiment relates to energy expenditure of pigs. Dietary fiber in hybrid rye may increase satiation and reduce physical activity, therefore decreasing the maintenance energy requirement of pigs fed hybrid rye. Thus, if group-housed finishing pigs fed hybrid rye exert less energy for physical activity than pigs fed corn, the growth response of pigs may not differ even if the metabolizable energy content in hybrid rye is truly less than in corn.

When hybrid rye substituted barley in diets for grow-finish pigs, carcass weight and slaughter value were greater for the pigs fed hybrid rye (Schwarz et al., 2015). In another experiment, when portions of barley were replaced with hybrid rye, backfat thickness was reduced in pigs fed rye, but no differences in other carcass traits were observed (Bussières, 2018). Similarly, most carcass traits were not affected by hybrid rye inclusion in an experiment when hybrid rye was added to diets at the expense of wheat (Smit et al., 2019), and the same was true for gross carcass characteristics in the present experiment when hybrid rye replaced corn. Although organ weights were greater as the inclusion of hybrid rye in the diet increased, carcass yield was not affected. The reason for heavier kidney and liver weights may be due to greater demand for the metabolism of excess dietary N in the diets containing hybrid rye. Although meat pH, marbling, and firmness did not differ among treatments, color of loins (visual) and backfat (instrumental L*) was lighter for pigs fed greater amounts of hybrid rye, and similar effects have been observed when barley replaced 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 greater abundance of bitter-tasting phenolic compounds in hybrid rye grain (Grosch and Schieberle, 1997; Heiniö et al., 2003; Poutanen et al., 2014), although flavor scores for loins were inherently low for all samples.

Conclusions

Feed intake trended downward with greater inclusions of hybrid rye in the grower and late finisher diets; thus, it seems that the unfamiliar flavor and greater dietary fiber in hybrid rye may have been stronger drivers of feed intake than dietary energy level in the present experiment. It is possible that the reduction in ADFI and ADG upon introduction to hybrid rye in grower diets may be ameliorated if pigs are introduced to hybrid rye earlier in life. Feed efficiency was not hindered by inclusion of hybrid rye in diets, indicating that the ingredient was well utilized by grow-finish pigs, and most carcass traits did not differ among treatments, although organ weights were heavier. Ultimately, results of the present experiment support the hypothesis that hybrid rye may be included in diets for growing-finishing pigs at the expense of corn without compromising overall growth performance.

Tables

Table 8.1. Ingredient composition (as-is basis) of experimental diets with increasing replacement of corn with hybrid rye

	Grower (d 1 – 35)[1]				Early finisher (d 35 – 70)[1]				Late finisher (d 70 – 97)[1]			
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[2]	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]The percentages indicate the amount of corn that was replaced with hybrid rye in the diets.

Table 8.1 (cont.)

[2]The vitamin-micromineral premix provided the following quantities of vitamins and microminerals per kg of complete diet: Vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 as cholecalciferol, 2,208 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride,0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper sulfate and copper chloride; Fe, 126 mg as ferrous sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese sulfate; Se, 0.3 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc sulfate.

Table 8.2. Analyzed composition (as-is) of hybrid rye and experimental diets with increasing replacement of corn with hybrid rye

	Grower (d 1 – 35)[1]				Early finisher (d 35 – 70)[1]				Late finisher (d 70 – 97)[1]				Hybrid
Item	0%	33%	66%	100%	0%	33%	66%	100%	0%	33%	66%	100%	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
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

Table 8.2 (cont.)

	Grower (d 1 – 35)[1]				Early finisher (d 35 – 70)[1]				Late finisher (d 70 – 97)[1]				Hybrid
Item	0%	33%	66%	100%	0%	33%	66%	100%	0%	33%	66%	100%	rye
Amino acids, %													
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 with hybrid rye in the diets.

[2]GE = gross energy; IDF = insoluble dietary fiber; SDF = soluble dietary fiber; TDF = total dietary fiber; AEE = acid-hydrolyzed ether extract; ND = not detected.

[2]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).

Table 8.3. 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					*P* – values	
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							
Grower, day 1 to 35	0.91	0.86	0.83	0.82	0.024	0.006	0.367
Early finisher, day 35 to 70	1.05	1.09	1.07	1.07	0.031	0.733	0.472
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							
Grower, day 1 to 35	1.75	1.67	1.57	1.57	0.048	0.005	0.355
Early finisher, day 35 to 70	2.66	2.66	2.62	2.56	0.079	0.356	0.675
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							
Grower, day 1 to 35	0.52	0.52	0.53	0.52	0.008	0.830	0.944
Early finisher, day 35 to 70	0.40	0.41	0.41	0.42	0.009	0.067	0.753
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 8 observations.

Table 8.4. 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					*P* – values	
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, 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[2], %	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[3]	3.19	2.94	2.94	2.75	0.106	0.011	0.765
Visual marbling[4]	1.61	1.60	1.39	1.90	0.242	0.386	0.126
Subjective firmness[5]	3.11	2.97	3.02	2.91	0.120	0.315	0.913
Lightness, L*[6]	46.33	47.22	46.75	48.19	0.933	0.232	0.772
Redness, a*[6]	8.04	8.35	8.04	7.88	0.504	0.705	0.599
Yellowness, b*[6]	4.54	5.00	4.72	4.39	0.391	0.667	0.295

Table 8.4 (cont.)

	Corn replacement rate					*P* – values	
Item	0%	33%	66%	100%	SEM	Linear	Quadratic
Backfat color							
Lightness, L*[6]	72.42	72.72	73.17	73.34	0.483	0.036	0.839
Redness, a*[6]	3.76	4.00	3.83	3.90	0.412	0.866	0.785
Yellowness, b*[6]	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[7]							
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 7 to 8 observations.

[2]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.

[3]National Pork Producers Council color based on the 1999 standards measured in half point increments where 1 = palest and 6 = darkest.

Table 8.4 (cont.)

[4]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.

[5]National Pork Producers Council firmness based on the 1991 scale measured in half point increments where 1 = softest and 5 = firmest.

[6]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.

[7]Sensory characteristics were scored 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.

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CHAPTER 9: Conclusions

Hybrid rye is a suitable feed ingredient for pigs of all physiological stages. As a cereal grain, hybrid rye provides similar quantities of standardized ileal digestible amino acids, slightly less metabolizable energy, and a greater amount of fermentable dietary fiber to diets compared with corn. Results of experiments presented in this dissertation indicate hybrid rye may replace a majority of corn in diets for growing and reproducing pigs without negatively impacting average daily gain.

Specifically, up to 75% of corn may be replaced with hybrid rye in diets for gestating and lactating sows without hindering sow or litter performance, and replacing 25 to 50% of corn in diets for sows resulted in improved lactation performance. Although the digestible and metabolizable energy is approximately 170 kcal/kg (dry matter basis) less in hybrid rye than in corn when determined in gestating sows, this difference is less than when determined in growing pigs due to the greater fermentative capacity of sows.

Nursery pigs and growing pigs prefer diets containing corn to diets containing hybrid rye when given the choice; however, it is likely that early and step-wise introduction of hybrid rye to a diet is an effective strategy to allow pigs to adapt to eating the novel ingredient. Weanling pigs performed well when up to 60% of corn was replaced with hybrid rye in diets in the first week after weaning. In week 2 and 3 post-weaning, up to 90% of corn may be replaced with hybrid rye in diets without influencing growth performance, including feed efficiency. In nursery diets fed during weeks 4 and 5 post-weaning, all of the corn may be replaced with hybrid rye without jeopardizing average daily gain; however, pigs will likely consume more feed to compensate for the reduced metabolizable energy in hybrid rye compared with corn.

Growing and finishing pigs may be fed diets with up to 100% substitution of corn with hybrid rye without influencing average daily gain. In the late finishing period, however, the dietary fiber from hybrid rye may increase gut fill and feelings of satiety, thus restricting feed intake. As was true in sows, hybrid rye was well utilized by finishing pigs overall, and gain:feed did not differ among treatments. Carcass traits were generally unaffected by dietary inclusion of hybrid rye, although organ weights were heavier from pigs fed hybrid rye.

Overall, the differences in growth performance observed in pigs fed hybrid rye compared with corn can largely be attributed to the greater dietary fiber and reduced metabolizable energy content in hybrid rye. Sows appeared to benefit from being fed hybrid rye compared with corn, likely because consuming the bulkier gestation diet better equipped the sows to transition to *ad libitum* feed intake in lactation and avoid excess negative energy balance. Nursery pigs consumed more feed when hybrid rye was included in great amounts, so supplementing diets containing hybrid rye with an additional fat source may help ameliorate the expected reduction in feed efficiency. Conversely, growing and finishing pigs exhibited no differences in gain:feed, so it appears to be more important to adapt pigs to hybrid rye early to avoid an initial reduction in feed intake.