The Impact of Increasing Dietary Levels of Hybrid Rye on Growing-Finishing Pig Performance, Carcass Characteristics, and Meat Quality

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THE IMPACT OF INCREASING DIETARY LEVELS OF HYBRID RYE ON GROWING-FINISHING PIG PERFORMANCE, CARCASS CHARACTERISTICS, AND MEAT QUALITY

BY

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A thesis submitted in partial fulfillment of the requirements for the

Master of Science Major in Animal Science

South Dakota State University

2023

THESIS ACCEPTANCE PAGE

Caitlyn Rose Sullivan

This thesis is approved as a creditable and independent investigation by a candidate for the master's degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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ACKNOWLEDGEMENTS

As my time at South Dakota State University comes to an end, I have numerous individuals to recognize. Along with their support in completing my degree, I credit these individuals for acknowledging my potential, even when I couldn't see it. I have the uttermost respect for each of you and thank the Lord that our paths have crossed. I'm indebted to you all for your influence on my life and for helping me recognize the person I want to be.

First, I would like to acknowledge the National Pork Board for funding my thesis through the Pork Scholar Program and my advisor, Dr. Bob Thaler, for selecting me as the individual to represent this research. To Dr. Thaler, thank you for always believing in me and for the vast exposure in extension and academia. I am truly honored to be advised by "one of the greats."

I would also like to thank Pipestone Nutrition and Pipestone Applied Research for their dedication towards my thesis. I could not have successfully completed this research without the support of Dr. Kiah Berg and the Pipestone staff. To Dr. Berg, thank you for your guidance and for the opportunity to be mentored by you. I also want to thank Dr. Molly McGhee for her preliminary work on hybrid rye as a feed ingredient, which supported this investigation in a commercial setting. To Dr. Carly Rundle from KWS Cereals, thank you for sharing your knowledge as a swine nutritionist and advocate for hybrid rye. I'm very appreciative of your insight and our developed friendship.

Secondly, I want to acknowledge my other committee members: Dr. Eric Weaver, Dr. Gary Hatfield, and Dr. Tong Wang. Thank you for your time in preparing my thesis and serving on my committee. To Dr. Weaver, I will be forever grateful for your influence on my understanding of the industry and for always addressing my persistence with logic and encouragement. I would not be as educated in diet formulation, or the techniques used in production without your guidance. I also want to extend my gratitude to the other professors in the department: Dr. Crystal Levesque, Dr. Jinsu Hong, Dr. Jorge Perez-Palencia, Dr. Julie Walker, and Dr. Judson Grubbs. Thank you for your guidance during my program and always being there to listen, whether it be about pigs or life itself. I am very thankful for the opportunity to associate with such renowned individuals as yourself. To Dr. Levesque, I can't thank you enough for your assistance in completing my thesis and inspiration to always seek a deeper understanding. To Dr. Hong, words cannot describe how grateful I am for your supervision in completing additional research and the influence you've had on my ambitions to pursue a Ph.D. Thank you for persistently supporting me as a mentor and friend.

I also want to thank my colleagues for the countless memories and their acquaintances through my time at SDSU. To Shannon Dierking, Emily Fowler, Joel Kieser, and Anlly Fresno Rueda, I am truly grateful for our friendship and wish you nothing but the best in life. To Shannon Dierking, I can't emphasize enough how much I cherish our friendship and for always being in my corner with compassion and inspiration. I aspire to be an individual such as yourself and cannot wait to see what you accomplish. To Emily Fowler and Anlly Fresno Rueda, thank you for always being an outlet for my troubles and the encouragement you provided in completing my degree.

To the beef group: Dr. Zach Smith, Dr. Warren Rusche, Forest Francis, Becca Grimes, Erin Gubbels, Thiago Ribeiro, Alex Kelly, and Tommy Norman, thank you for allowing me to fulfill my niche in ruminant nutrition and for your friendships that I will cherish indefinitely.

To my family, thank you for always pushing me to follow my dreams and your support in my endeavors. To my parents, Meledy, and Dwayne Sullivan, I owe it to you both for teaching me to never back down from the challenges of life and to always seek out the greater good.

To my boyfriend, Justin Schneider, thank you for always being my #1 and never letting me take myself too seriously. I could not ask for a more supportive partner and would not be able to do any of this without you. To Samantha Jacquin, thank you for always being there, even when it was from a distance. I am very grateful for our childhood friendship that has flourished into adulthood.

To my friends from Mizzou, I will always be grateful for your support in continuing my education. To Tawnie DeJong, Hannah Twenter, Dr. Tim Safranski, and Dr. Bryon Wiegand, thank you for pushing me to be the best version of myself and for the inspiration I needed to pursue graduate school.

“ Our potential is one thing. What we do with it is quite another.”

– Angela Duckworth

TABLE OF CONTENTS

LIST OF TABLES

1.0 LITERATURE REVIEW

1.1 Introduction

What is Sustainable Agriculture?

Sustainable agriculture is a concept historically associated with farming, but as both crop and livestock production have increased in scale and the use of technology, many people with no actual “ag experience” believe producers’ focus has shifted from sustainability to profit. However, that is not the case, and with the responsibility of feeding 9 billion people with fixed or decreasing resources, one could argue that the emphasis on sustainability has actually increased. The goals of *sustainable agriculture* revolve around meeting society’s present food and textile needs without compromising the ability of future generations to meet their own needs (Feenstra, 2021). This definition provides a unique opportunity for pork producers to join with producers in other commodities to create a “systems approach” to promote sustainability metrics, which benefits both society and agriculture.

As the impact of animal agriculture on the environment continues to be more scrutinized, it is imperative that pork producers utilize methods that optimize pig performance and economics, while at the same time preserving or even improving our natural resources. Along with practicing land conservation, producers must also utilize feeding programs that reduce the amount of nutrients (i.e., nitrogen, phosphorus) excreted into the environment (Vonderohe et al., 2022) and improve soil health. To help achieve these goals, producers are tasked to use alternative cereal grains in swine diets that promote diversified cropping systems and improve the agronomic supply chain (Honeyman, 1996). This interaction between swine production and cropping systems is critical because of the impact they both have on sustaining the environment and maintaining the economics for both industries.

National Pork Board Efforts in Sustainability

The We Care program was established in 2008 by a collaboration of the National Pork Board, the National Pork Producers Council and state pork producer organizations (We Care, 2021). This program was formed to promote sustainable practices in each area of the swine industry. Another tenet of the We Care program is “continuous improvement”, so it is important that research continues in all areas of sustainability, not only to understand their impact on swine production, but to identify and quantify these sustainable practices. We Care is a pledge of six principles that continuously evaluates production methods, with the focus on the ethical advancement in farms, communities, food service, and the ecosystem. These guidelines identify obligations for food safety, animal welfare, producers, the environment, public health, and the community. These commitments highlight the industry’s goals and effectiveness in preserving the use of carbon, water, and land.

At the 2022 Pork Forum, the National Pork Board made increasing the sustainability of pork production their third, highest priority, with the first priority focusing on keeping African Swine Fever out of the U.S and the second being the expansion on the “Real Pork Trust and Image” campaign (Shike, 2022). When these goals were created, it was emphasized that producers should focus on areas of sustainability that are involved with We Care. In the last six decades, pork producers have decreased the amount of land (75%), water (25%), and energy (7%) needed to produce pork, which has resulted in an 8% total reduction on their environmental footprint (We Care, 2021). This reinforces the fact that pork producers have been practicing environmental sustainability for years, but in order to demonstrate this to the public, metrics have to be created to scientifically document these changes. To do this, the Life Cycle Assessment (LCA) was created (Johnson et al., 2022). This holistic approach evaluates the cumulative environmental impact of swine production (i.e., feed processing, stages of production, transportation, harvesting, packaging, distribution, retail, consumption/ removal) (Mackenzie et al., 2016). This assessment is divided into sections to indicate the individual life cycles for carbon, land, and water (Johnson et al., 2022). With this tool, producers are able to adjust production techniques to reduce their farm's carbon footprint and promote nutrient recycling.

Areas of Swine Production Impacting Sustainability

The U.S. Environmental Protection Agency (EPA) states that "to pursue sustainability is to create and maintain conditions under which humans and nature can exist in productive harmony to support present and future generations" (Council, 2011; Vonderohe et al., 2022). With this call to action, producers are eager to embrace this movement to improve the environmental sustainability of their systems, while also promoting the economic sustainability of their operations for future generations.

Swine feeding programs represent 75% of the cost of raising pigs (Menegat, 2019) and is an area of pork production that impacts several of the principles previously mentioned. The pillars of community, environment, and animal well-being are all impacted by swine nutrition (We Care, 2021). With these established measures, there is an opportunity to optimize feeding programs with the inclusion of new ingredients that preserve soil health and maintain or decrease input costs. In current pork production, 50-60% of the environmental footprint is attributed to the production of crops used in swine diets (We Care, 2021). To simplify sustainability for crop production, goals have been created that emphasize a practice known as *Conservation Agriculture* (CA) (Friedrich et al., 2012). This procedure focuses on the innovative management of soil, land, water, and nutrient utilization. The aim of CA is to implicate three, alternative management techniques in crop production that include direct planting with minimal soil disturbance (i.e., no-till), cover crop application to reduce the duration of bare soil exposure to the atmosphere, and crop rotation to benefit from residual nutrients (i.e., nitrogen) (FAO; Hobbs et al., 2008; Pittelkow et al., 2015).

This thesis will focus on one factor of improving sustainability in the swine industry, specifically with the use of hybrid rye and its impact on agronomic sustainability, pig growth performance, carcass characteristics, and meat quality.

1.2 What is Hybrid Rye?

Historically, rye (*Secale cereale*) has not been considered as a "suitable" feed ingredient in swine diets because of the challenge of the ergot alkaloids included in the grain (McGhee, 2019). Ergot toxicity effects all stages of swine production with symptoms that include lethargy, abortions, impaired hepatic function, and suppressed reproductive abilities (Dänicke and Diers, 2013; Coufal-Majewski et al., 2016; Waret-Szkuta et al., 2019; Arroyo-Manzanares et al., 2021). A ration with ergot contamination exceeding 4.85 mg total alkaloids/ kg of diet can reduce growth performance by 6% in growing pigs (Mainka et al., 2005). In a field study that evaluated ergot-contaminated, wheat based-diet that contained 3.49 mg/kg ergot alkaloids in gestation diets (d 10-15) and 8.06 mg/kg of ergot alkaloids in lactation diets (d 3-4), 65% of the sows had agalactia, with a high percentage of litter mortality rates across treatments (< 76%) (Waret-Szkuta et al., 2019).

To alleviate the negative association of ergot in cereal rye, a seed genetic company (KWS, Germany) in Europe has developed a series of rye cultivars that demonstrate superior heterosis, which accelerates the pollination stage, thereby reducing the opportunity for ergot alkaloids to infiltrate the stigma (Schwarz et al., 2014; Smit et al., 2019).

In developing hybrid rye, four cultivars have been produced: Bono, Serafino, Eterno, and Tayo (KWS, 2022). These varieties were established by cross-breeding two, genetically different parental rye lines that enable the stigma to produce a large amount of pollen, which accelerates the reproductive stage (Geiger and Miedaner, 1999). This trait, known as the Pollen Plus gene, improves the plant's ability to protect itself from mycotoxin contamination, which ultimately reduces the level of ergot alkaloids observed in the harvested crop (KWS, 2022).

Along with disease resistance, hybrid rye is also drought tolerant and can be grown in various conditions and soil types (e.g., clay, silt, sand), which makes this small grain a much more viable option for growers in the U.S. Corn Belt (Jürgens et al., 2012).

Since many of the agronomic and economic conditions in Europe are different from those in the U.S., it is important to determine the impact of hybrid rye in a cropping system in the Corn Belt before unbiased recommendations can be made on its use.

A Production Guide to Grow Hybrid Rye

The planting date for hybrid rye will vary within the growing region, but is commonly between early September to mid-October, when soil temperatures are below 15˚C (KWS, 2022). For optimal growth, hybrid rye should be planted in fields with loamy soil, where the pH ranges from 5.6 to 7.0 (Wiersma et al., 2021). A conventional drill should be used with a plant depth of approximately ten times the diameter of the seed (2.03 cm max) (KWS, 2022). The seeding rate of hybrid rye for grain production ranges from 68.18 kg/ha to 102.27 kg/ha (Bruening, 2015). After soil testing and planting is complete, the initial, fall fertilizer application will vary on residual nutrients, but a typical rate of commercial application includes 117.88-157.18 kg/ha of nitrogen (N), 22.45-28.07 kg/ha of phosphorus (P) and 44.9-56.14 kg/ha of potassium (K) (KWS, 2022). The recommended spring application of N is 67.36 kg/ha (Bruening, 2015). It's crucial to apply N in a timely manner (e.g., early March) to eliminate any risk for lodging (i.e., permanent displacement of stem from upright position) or disease (Bruening, 2015; Dahiya et al., 2018).

Harvest occurs between early July and mid-August in the U.S., when the relative moisture content of the grain is below 18% (KWS, 2022). Depending on the variety selected, hybrid rye can reach harvest maturity within a week of winter wheat (Bruening et al., 2015). Commercial hybrid rye can also yield 30-40% more than open-pollinated wheat varieties (Wiersma et al., 2021). The standard test weight for rye is 69.9 kg/hL in comparison to wheat (74.9 kg/hL) (Bruening et al., 2015). In a study that evaluated the differences in hybrid rye cultivars as compared to conventional rye, it was observed that hybrid rye had a 30% increase in grain yield (3.50 Mg/ha; 4.96 Mg/ha) and a significant reduction in lodging (51%; 1%), respectively (Bruening et al., 2015).

Integrating Hybrid Rye as a Cover Crop

Most farmers in the U.S. Corn Belt utilize a corn-soybean (CS) rotation to maximize economic return (Feng et al.,2020), which also provides low-cost, feed ingredients for swine producers. However, the long-term effects of using a CS rotation can be detrimental to land integrity (e.g., nutrient leaching, field destabilization, water pollution), as this cycle can jeopardize nutritive levels (i.e., nitrogen) and put soil stability at risk for erosion (Philip Robertson et al., 2014; Feng et al., 2020).

Traditionally, agriculture contributes 30% of the total greenhouse gases related to climate change (IPCC, 2007; Friedrich et al., 2012). Even though some areas in the U.S. are utilizing no-tillage in crop production, the majority of the corn and soybeans produced are planted conventionally, which can result in a significant reduction on field conservation, due to continual soil disturbance (Horowitz et al., 2010; Halvorson and Schlegel, 2012; McDaniel et al., 2014; Chatterjee et al., 2016; Singh et al., 2021). To alleviate this problem, some growers are using cover crops to, not only influence conservational sustainability, but to support the agronomics of agriculture (Friedrich et al., 2012).

Cover crops have the ability to enhance soil health, water quality, organic matter, and disease resilience (Clark, 2019). Cover crops are commonly rotated in a CS cropping system to reduce the risks of erosion and pest inhabitance, along with the ability to improve residual nutrients (McDaniel et al., 2014). When cover crops are used (i.e., oats, winter wheat), research has shown a 6% increase in corn yield and a 4% increase in soybean yield (Singh et al., 2021). Although the potential for hybrid rye to preserve soil conditions and improve yields for CS rotations exists, growers are still reluctant to plant hybrid rye, due to the uncertainty of a consistent market for the grain (Friedrich et al., 2012).

To promote hybrid rye production using a comparison to conventional rye, previous literature has investigated cereal rye as a cover crop because of its ability to recover residual nutrients (i.e., nitrogen) (48% N) with fall application, compared to leguminous cover crops (i.e., crimson clover, hairy vetch) (8% N; 9% N) (Shipley et al., 1992; Strock et al., 2004; Bruening, 2015). It has also been reported that the concentration of nitrate-nitrogen leached from a corn-cereal rye cropping system was significantly lower than fields that practiced winter fallow after corn harvest (McCracken et al., 1994; Strock et al., 2004).

In evaluating the input costs of planting cover crops, researchers in one study used different cultivars (corn, soybeans, peas, winter wheat, oats, spring wheat) to compare the expenses (i.e., seed, machinery, fertilizer, herbicides) and net return in a 4-year rotation (2013-2016) versus a continuous CS rotation (Feng et al., 2020). The total cost of a CS rotation for each year was $432.88/ha as compared to the diversified cropping systems which averaged $382.31/ha. The higher input costs from a double-crop rotation were attributed to higher seed, fertilizer, and machinery costs to plant and harvest corn and soybeans. However, even with the elevated input costs, profits were still higher ($791.43 ha) for a CS rotation, than for the diversified fields ($720.04 ha), which were based on current prices at that time. Subsequently, due to the fluctuation of input costs and market prices for grain production, producers need to consider current values when calculating the profitability of hybrid rye.

Even when considering the lower input cost of growing hybrid rye compared to corn ($400/ha; $765/ha) (KWS, 2022), hybrid rye lacks the ability to produce the same yields of corn (4.96 Mg/ha; 6.18 Mg/ha), which reduces profitability for growers in the U.S. Corn Belt (Bruening, 2015; Feng et al., 2021).

Conclusion

For a cropping system to be sustainable, there also has to be economic gain (Singh et al., 2021). Growers are encouraged to diversify their cropping systems because of the cost variation and environmental impact involved with continuous CS rotations. To promote cover crop production, it's crucial that a stable market be created for these crops, which can be achievable if the swine industry increases small grain inclusion in their diet formulation. This support could also lead to a reduction on the total impact of the environmental footprint for U.S. swine production.

1.3 Including Small Grains in Swine Diets

Alternative Diet Formulation

The value of an alternative ingredient in swine diets is based on the impact it has on the three, most expensive factors in diet formulation: energy, lysine, and phosphorus content (Boggess et al., 2018). Although traditional swine diets contain a high percentage of corn, feeding small grains (i.e., barley, rye, triticale, wheat) can meet nutrient recommendations, while also reducing feed cost (Boggess et al., 2018). Depending on the source (i.e., rye, triticale, wheat), pigs fed diets replacing corn with 100% small grains can perform similar to pigs fed corn-based diets (Sullivan, 2005). Subsequently, the lower caloric content of small grains (i.e., 5-10%) can result in a poorer feed conversion, as pigs consume more of the diet to meet energy requirements. Even though pigs have the capability of consuming a wide range of feedstuffs, there is a lack of literature to support a complete replacement of corn with hybrid rye in a commercial setting (Bussières, 2018; McGhee et al., 2021).

While pork producers in Europe commonly feed small grains to pigs, it has been observed that hybrid rye may be a suitable feed ingredient for pigs because of its high protein content and lower fiber constituents (Schwarz et al., 2014). Along with supporting nutrient composition, the feed cost per pig when replacing barley or wheat with hybrid rye in swine diets in Europe may be more comparable to swine diets in the U.S. that include corn (Schwarz et al., 2014; Smit et al., 2019). Even with this potential benefit, pork producers in the U.S. are still reluctant to feed rye to pigs because of the previous antinutritional factors observed in conventional rye (i.e., mycotoxin exposure) (Bussières, 2018).

Metabolizable Energy

The metabolizable energy (ME) content of an ingredient is essential in determining the feasibility of it being included in swine diets. The efficiency of energy utilization required by the swine species is determined on the amount of fat and protein deposition needed for growth (Lewis A., 2001). The exchange of energy needed for growth in pigs is 1.12 kcal per gram of muscle tissue gained (Lewis A., 2001). Subsequently, due to their nutrient profiles, small grains contain lower levels of energy when compared to corn (Sullivan, 2005). McGhee (2019) reported that in growing pigs, the ME content of hybrid rye was 3153 kcal/kg, as compared to 3274 kcal/kg for corn.

Amino Acids

Once the caloric value is established, the ratio of amino acids (AA) needed in the diet can be assessed. Recent research has shown that the protein content in or hybrid rye (Bono) (8.65% CP) is relatively higher than corn (7.20% CP) (McGhee, 2019). Even though CP is a traditional method used in diet formulation, current commercial diets are based on AA "bioavailability," which is defined as "the proportion of ingested dietary AA that is absorbed in a chemical form that renders these AA potentially suitable for metabolism or protein synthesis" (Batterham, 1992; Lewis and Bayley, 1995; Stein et al., 2007).

Previously, the bioavailability of AA was determined using a slope-assay, but due to the cost related to this analysis, it is common in diet formulation to determine the AA digestibility by subtracting the percentage of dietary AA from the AA content recovered after absorption in the small intestine (NRC, 2012). The digestibility of AA reflects the ability for enzymatic hydrolysis and microbial fermentation of degradable proteins to occur in the gastrointestinal lumen (Fuller, 2003; Stein et al., 2007). It's important to feed cereals that provide high concentrations of SID AA, so that efficient absorption can occur (Lewis A., 2001). Two measurements (apparent ileal digestibility (AID) and the standardized ileal digestibility (SID)) are used to indicate the bioavailability of AA (Stein et al., 2007; Zhang and Adeola, 2017). The rate of AID is determined by the net disappearance of AA, relating to the total contents of AA in digesta (Stein et al., 2007). Because apparent ileal digestibility does not consider the endogenous AA produced intestinally, standardized ileal digestibility (SID) has been practiced to determine AA requirements for pigs (Stein et al., 2007; NRC, 2012).

Cereal grains generally provide 40-50% of the AA needed for pigs (Lewis A., 2001). Consequently, diets that include higher levels of corn can be limited on the amount of essential AA, specifically lysine, threonine, and tryptophan, if balanced on a CP basis. To meet nutrient recommendations, corn-based diets are formulated to include a source of protein (i.e., soybean meal) to provide "ideal" AA ratios (NRC, 2012). Since small grains can contain 30-50% more lysine than corn (Boggess et al., 2018), this can reduce the amount of soybean meal that must be added to the ration by approximately 50.12 kg/Mt (Sullivan, 2005).

When assessing the total AA content of hybrid rye, McGhee (2019) concluded that the lysine content of hybrid rye (0.36%) was greater than that of corn (0.27%). The concentrations of threonine (0.29%) and tryptophan (0.08%) were also greater in hybrid rye than corn (0.27%; 0.06%, respectively) (McGhee, 2019). Because corn-based diets are dependent on supplemental protein sources to provide adequate essential AA levels, there may be a cost-effective benefit to including higher levels of hybrid rye in swine diets, thereby reducing the amount of supplemental protein added to the diet.

Using SID, McGhee (2019) reported that the SID coefficients for lysine (62.1%), threonine (64.0%), and tryptophan (71.6%) of hybrid rye to be less than that of corn (78.4%; 82.1%; 88.9%, respectively). Even though the rate of SID was lower for these specific AA, the amount of available AA for lysine and tryptophan was still greater in hybrid rye (2.2 g/kg; 0.6 g/kg than corn (2.1 g/kg; 0.5 g/kg, respectively) (McGhee, 2019). These results reflect the higher CP content in hybrid rye than corn (8.65%; 7.20%). In contrast, McGhee (2019) reported that the total SID threonine was higher in the corn (2.2 g/kg) sourced, compared to hybrid rye (1.9 g/kg).

Calcium and Phosphorus

Calcium (Ca) and phosphorus (P) are both essential minerals involved in skeletal development and physiological function. Cereal grains are common sources of P, which is stored primarily as phytic acid or phytate (Zhai et al., 2022). The conundrum is that most plant-sourced P is poorly digestible by monogastric animals unless phytase is added to the diet (She et al., 2017). The phytate-bound P is only partially degradable because of the insignificant amount of phytase secreted from the pig's gastrointestinal tract (Ajakaiye et al., 2003; She et al., 2017). It is common practice in diet formulation to include exogenous phytase to reduce the amount of P excreted in manure (Selle and Ravindran, 2008).

When McGhee (2019) assessed the total P content in hybrid rye, it was considerably higher (0.26%) than corn (0.23%) (McGhee, 2019). Subsequently, the standard total tract digestibility of P without phytase is greater in hybrid rye (48.7%) than corn (24.9%) (McGhee, 2019). Using these digestibility coefficients, the amount of non-phytate P is greater in hybrid rye than corn (0.06%; 0.04%, respectively). This could be due to the greater amount of intrinsic phytase in hybrid rye (3,000 FTU) as compared to corn (<70 FTU). McGhee (2019) also observed that hybrid rye had 0.03% total Ca, which was greater than corn (0.01%).

Utilizing Hybrid Rye in all Stages of Production

In an effort to improve sustainability, swine producers are considering ingredients from local ag systems, specifically from growers that have reduced their reliance on cash crops, by diversifying their field throughput with small grains (Jarrett and Ashworth, 2018). The challenge of including small grains in commercial diets is that these feedstuffs are typically lower in energy because they contain higher levels of dietary fiber (DF) and lower levels of fat/oil (Jarrett and Ashworth, 2018; Weng, 2020). The DF percentage is specific to the non-digestible carbohydrates (i.e., non-starch polysaccharides, resistant starch, non-digestible oligosaccharides) and lignin concentration in the ingredient (Jørgensen et al., 2007; Li et al., 2021).

As hybrid rye production continues to grow in the northern hemisphere, the U.S. swine industry needs to consider the effect of the DF content of hybrid rye (15.16%) in all stages of production (McGhee, 2019). Previous research has shown a beneficial influence of DF on the pig's microbiome by fermenting the fiber constituents (i.e., protecting the luminal epithelium, producing volatile fatty acids, reducing intestinal pH, producing metabolites for immune support) (Tremaroli and Bäckhed, 2012; Blander et al., 2017; Yamashiro, 2018; Li et al., 2021).

Gestation and Lactation

The feeding program during gestation is critical for fetal development and growth of corresponding tissues (i.e., placenta, uterus, mammary tissue) (NRC, 2012). Along with meeting nutritional demands to support sow maintenance and neonatal growth, there is also a growing concern on how feeding programs impact animal well-being (Holt et al., 2006; NRC, 2012). Gestation feeding programs that regulate feed intake are at risk for stereotypic behaviors in sows (Holt et al., 2006). These behaviors can include bar biting, sham chewing (i.e., chewing motions not associated with eating) and licking inanimate objects when feeders are empty. This reliance on concentrated diets (i.e., corn-soybean meal) is to prevent excessive weight gain that can cause complications during farrowing (Meunier-Salaün et al., 2001; Jensen et al., 2012). If gestation diets aren't regulated on semi-ad libitum access (i.e. fed a greater amount of a lower, nutrient-dense diet per day), it can cause farrowing locomotion difficulties, along with a reduction in piglet survival (Guillemet et al., 2006).

Utilizing ingredients that have a higher percentage of DF have the ability to increase satiety because of gut-fill and the influence on hindgut fermentation to absorb the short-chain fatty acids derived from fiber constituents (i.e., non-starch polysaccharides, non-digestible oligosaccharides, resistant starch) (Serena et al., 2009; Jensen et al., 2012; Weng, 2020; Li et al., 2021). Depending on the physiochemical properties of the source, the subsequent, gastrointestinal reaction that occurs in the hindgut to break down the DF can reduce the risk of constipation, stimulate fullness, and maintain sow performance (i.e., body condition score, parturition length, piglet survivability) (Li et al., 2021). The DF component of hybrid rye (15.16%) may cause similar effects in sows by reducing hunger and stimulating satiation.

In order to prevent extensive mobilization of lipid and protein stores during the lactation phase, it is critical to stimulate lactation feed intake to maintain sow performance (NRC, 2012). In commercial production, it is commonly practiced to regulate feed intake during gestation, that are lower in caloric value and have greater bulk density to support gut fill, which stimulates sows to increase average daily feed intake (ADFI) during lactation to achieve the same sensation of satiety observed during pregnancy (Lewis A., 2001). Changing the energy balance in prolific sows can have long-term effects on reproductive longevity (NRC, 2012). If the desired feed consumption does not occur, the sow will catabolize fat and muscle tissue to provide nutrients needed for milk production, which consequently diminishes the sow's ability to successfully re-breed (Guillemet et al., 2006). The goal of a lactation diet is to provide the sow with an energy-dense ration that supports ad libitum intake to maximize her maternal abilities (i.e., milk production, litter performance, reproductive performance) (NRC, 2012).

Providing diets with higher levels of DF can stimulate satiation during pregnancy because sows take longer to consume the bulky diet. This feeding technique has been utilized to prepare sows for ad libitum feeding during lactation (Guillemet et al., 2006). Weng (2020) investigated different fiber sources (wheat bran, rice hulls, soy hulls) and the comparable effects on sow and litter performance when feeding increasing DF (4.08%; 9.22%; 10.06%) sources during gestation and lactation. Even though there was no dietary effect on initial sow body weight (BW) during gestation (113.4 ± 0.21 days), a linear increase was recorded for sows to gain more weight when fed rice hulls (25.5 kg), compared to sows fed wheat bran (22.0 kg) or soy hulls (21.8 kg). In contrast to this, there was a linear decrease on backfat (BF) thickness on d 80 and d 110 of gestation of sows fed rice hulls (14.8 mm; 15.2 mm), compared to sows fed wheat bran (16.1 mm; 17.8 mm), there was no dietary effect of feeding soyhulls or wheat bran (15.3 mm; 16.8 mm). Due to this reduction, the sows fed wheat bran had greater BF thickness (17.8 mm) at weaning (d 28). During lactation (d 1-28), Weng (2020) observed greater feed consumption in the sows fed soyhulls and rice hulls (126.77 kg; 133.66 kg) than the sows fed wheat bran (121.29 kg). Subsequently, the total litter weight gain of the sows fed soy hulls were greater (59.34 kg; 49.98 kg) than the sows fed wheat bran (51.58 kg) or rice hulls (49.98 kg) during the lactation phase (d 1-28).

In contrast, other researchers have observed a negative impact on sow productivity by supplementing high DF diets during gestation. When sugar beet pulp (120 g/kg diet) and alfalfa meal (170 g/kg diet) was fed during gestation (d 1-109) and lactation (d 1-28), there was a subsequent reduction in sow performance, as the sugar beet pulp reduced lactation feed intake and piglet birth weight and the alfalfa meal impaired milk protein content (Krogh et al., 2017; Jarrett and Ashworth, 2018). This negative impact of high DF diets on lactating sows may reflect an influence on satiation.

To compare the impact of DF in hybrid rye (15.16%) on sow performance, Sørensen and Nymand (2018) fed higher levels of hybrid rye in gestation (60%) and lactation (35%) diets and observed no effects on sow body size. In a similar trial, McGhee (2020) found no differences in average daily gain (ADG) or BW in sows, when hybrid rye replaced 25-70% of corn in gestating diets (7.5-22.5% hybrid rye inclusion) and lactation diets (10-30% hybrid rye inclusion). Even though the dietary treatments differed on rate of ME consumption, there was only a linear tendency for ADFI to decrease in pre-farrowing sows (d 106 gestation), with no impact on ADFI during gestation (d 7-105) or lactation (d 1-20) (McGhee, 2020). There was a linear and quadratic increase in the number of pigs weaned per litter as the inclusion of hybrid rye increased in the sow diets. The positive influence on the number of piglets weaned may reflect the quadratic response that was recorded on total milk production. McGhee (2020) recorded that milk yield peaked (208.0 kg) when the replacement rate of corn for hybrid rye reached 50% and decreased (188.9 kg) when the replacement rate of corn reached 75%.

Nursery Phase

During the nursery phase, piglets are highly susceptible to stressors due to the change in environment and diet composition (Pond and Houpt, 1978; Moeser et al., 2007; Smith et al., 2010; Kim and Duarte, 2021). These stressors can cause inflammation and oxidative stress, which significantly impacts nutrient digestibility and gastrointestinal health (Kim and Duarte, 2021). It's important for nutritional programs to consider utilizing ingredients with higher levels of DF because of the need to protect the mucosal barrier, while degrading DF into organic acids (i.e., butyrate, propionate, acetate) (Williams et al., 2017; Li et al., 2021). Depending on the rate of fermentation and the amount of organic acids produced from the DF source, luminal pH will decrease to break down the fiber constituents, which also reduces the prevalence of pathogens in the gut.

Hybrid rye has the potential to improve intestinal function because of the influx in hindgut fermentation to produce short-chain fatty acids (i.e., butyric acid), which lowers the pH and encourages microbial colonization (Zhao et al., 2013; Bach Knudsen et al., 2016; Bach Knudsen et al., 2017; McGhee and Stein, 2020). To address the effects of a hybrid rye (69.0%) replacement and control wheat (69.0%) diet during a *Salmonella* challenge (i.e., orally injected S. Typhimurium) in nursery pigs, it was reported that, even though there was no difference in mean bacterial counts within fecal samples of either, pelleted treatment group on d 1,3,5, or 7, there was a significant reduction (2.62 ± 0..18 log_{10} CFU/ g; 3.30 ± 0.50 log_{10} CFU/ g) in fecal *Salmonella* at d 14 and throughout the remainder of the trial (28 days) (Chuppava et al., 2020). Chuppava et al. (2020) also reported no differences between the experimental and control groups for BW or ADFI.

Similar to that of Chuppava et al. (2020), McGhee and Stein et al. (2021) found that increasing the inclusion of hybrid rye (0-50%) in corn-based, nursery diets (three-phase feeding program) had no impact on piglet BW or fecal scores. Contrary to the results of Chuppava et al. (2020) on feed consumption, the latter study reported that increasing the inclusion of hybrid rye caused a positive influence on ADFI during phase 3 and overall with a subsequent reduction on gain to feed ratio (G:F) (McGhee and Stein, 2021).

Even with these benefits, there is still insufficient data to be confident in the advantages of feeding hybrid rye to weanling pigs. However, it must be stated that it is essential for newly weaned pigs to consume adequate amounts of energy within the first 36 hours, post-weaning, for normal growth performance and survivability. While the DF in hybrid rye may improve gut health, it also reduces the caloric concentration of the diet, which can have a negative impact on piglet performance, especially within the first two weeks after weaning.

Growing-Finishing

Historically, growing-finishing pig diets do not include high levels of DF because of the negative impact on growth performance (Agyekum and Nyachoti, 2017). Even though growing-finishing pigs have the ability to ferment DF, there are concerns about the rate of energy lost to produce volatile fatty acids via hindgut fermentation, as well as the amount of volatile fatty acids that are actually absorbed by the large intestine (Grieshop, 2001; Kerr and Shurson, 2013). The caloric value of an ingredient fed during the growing-finishing phase can impact diet cost, growth performance, and carcass yield (Marçal et al., 2019).

Previous research has shown that if hybrid rye-based diets during the growing-finishing period of pigs are formulated to maintain energy content and AA digestibility ratios, there is no impact on pig performance. Increasing the inclusion level of hybrid rye (25-50%), while maintaining an isocaloric and isonitrogenous profile of wheat and barley control diets, had no impact on ADG, ADFI, or G:F during a four-phase feeding program (Bussières, 2018). In contrast, Schwartz et al. (2015) reported that increasing the inclusion of hybrid rye from 10 to 50% during the growing-finishing period (d 1- 110) caused a linear increase in BW (103.3 ± 14.6 kg; 108.0 ± 9.9 kg), ADG (86.7 ± 13.5 kg; 90.8 ± 9.6 kg), and ADFI (2.1 ± 0.2 kg; 2.3 ± 0.2 kg), with no impact on total G:F.

When replacing corn with hybrid rye at different rates (0%, 33%, 66%, 100%) during the growing-finishing period (d 1-97), McGhee et al. (2021) reported a linear reduction in ADG (0.91 kg; 0.86 kg; 0.83 kg; 0.82 kg) and ADFI (1.75 kg; 1.67 kg; 1.57 kg; 1.57 kg), with no impact of G:F during the growing phase (d 1-35). There was a quadratic increase in ADG (1.02 kg; 1.13 kg; 1.05 kg; 1.01 kg) as the replacement rate of hybrid rye for corn reached 33% and a linear tendency for ADFI to reduce (3.21 kg; 3.30

kg; 3.03 kg; 3.08 kg) as the inclusion of hybrid rye increased from 0 to 100% in the late-finisher phase (d 70-97).

To increase energy digestibility of hybrid rye, fiber-degrading enzymes can be included in swine diets (Smit et al., 2019). This can be challenging, though, because of the additional expense of adding exogenous enzymes. When Smit et al. (2019) compared the differences in increasing the inclusion of hybrid rye (15.66-65.93%) in wheat-based diets with and without supplementing an exogenous enzyme (1,400 units β-glucanase and 4,500 units xylanase per gram of product; 200g/kg diet) during the growing-finishing period (d 0-76), there was still a reduction in ADFI and ADG, regardless of enzyme inclusion, with no impact on BW or G:F overall. The supplemented enzyme only influenced ADG to increase by 20 g/d during the growing phase (d 0 -42). The results of this trial may conclude a positive effect of increasing the inclusion of hybrid rye during the growing phase, but there is still an inconsistency of supporting exogenous enzymes inclusion with feeding hybrid rye during the finishing phase.

Factors Impacting the Feeding Level of Hybrid Rye

Previously, pork producers have been reluctant to use rye in feeding programs, due to its susceptibility for ergot alkaloids, low carcass yield, and other anti-nutritional factors. The tolerance for ergot alkaloid contamination is as low as 100 µg per kg of grain (Coufal-Majewski et al., 2016; McGhee, 2019). Mycotoxins are produced during the act of fungal metabolism and impact the nutrient composition of cereal grains (Lewis A., 2001). Bussières (2018) observed that diets containing hybrid rye (10-25%; 20-50%) during the growing-finishing period (week 0-13) of pigs (30-135 kg) that contained 800 ppb of ergot alkaloids had no effect on ADFI, ADG, or G:F. However, it was also recorded that when the hybrid rye included contained 980 ppb of ergot, there was linear reduction on ADG and G:F during the same period and weight range of pigs (Bussières, 2018).

Because of the composition of rye, this small grain has to be further processed (i.e., ground), which can cause the diet to be dustier (Sullivan, 2005). This impact on particle size can also cause a reduction in palatability. Therefore, anything that reduces diet palatability will reduce feed intake, and ultimately decrease pig performance (Bussières, 2018).

Conclusion

Within the last decade, there has been increased research conducted in Europe on including hybrid rye in swine diets to improve sustainability metrics and reduce input cost (Schwarz et al., 2014). As the U.S. swine industry begins to emphasize sustainability in pork production, it's crucial that the total impact of feeding hybrid rye on pig performance in a commercial setting be determined.

1.4 Enhancing Pork Cutout Value with Feeding Hybrid Rye

Carcass Evaluation

Carcass evaluation is used in swine production to evaluate the traits that contribute to the economic value of pork products (Ray, 2004). The standard measures that are taken at hog procurement plants include expected yield (%), hot carcass weight (HCW), backfat (BF) thickness, and iodine value (IV). The HCW is measured after euthanasia, head and organ removal, and before entering the cooler (Hamilton et al., 2003). Carcass BF is determined by either a probe or caliper, which is placed between the 10^{th} and 11^{th} ribs. Carcass yield (%) can be calculated by dividing HCW by the live BW before slaughter [HCW/Market BW) x 100] (Caldara, F. et al, 2013). The IV is determined by the amount of unsaturation in the fatty acid profile of the carcass fat (Benz et al., 2011). The standard range for IV in commercial production is 70 to 75 g/ 100 g (Barton-Gade, 1987; Madsen et al., 1992; Boyd et al., 1997; Benz et al., 2011). To determine the fatty acid profile or IV, it is standard to use fat samples (approx. 5 grams) obtained from the inner, left side of the BF layer (Prieto et al., 2018). Each sample is measured on the ability for light to penetrate, using near infrared (NIR) spectroscopy (Balage et al., 2015). This instrument quantifies the variation of wavelengths in the reflection and is recorded in nanometers (nm).

Measuring Pork Quality

Influences on pH, color, texture, intramuscular fat, and consumer acceptance all affect the “quality” of pork. Understanding the eating experience of pork products is crucial in promoting consumption rates and economic sustainability for the swine industry.

Consumer purchasing decisions are related to the product’s color, texture, and display (i.e., excessive fat, water holding capacity) (Choe et al., 2016). To replicate this experience for research, it is standard to conduct a trained, sensory evaluation (LARMOND, 1976; Choe et al., 2016) This assessment is completed by trained, panelists that compare characteristics of the product to determine consumer acceptability (Wheeler et al., 1997; Warriss, 2000; Destefanis et al., 2008; Choe et al., 2016). Using a sensory panel can provide an objective measure of these attributes that may impact pork purchasing decisions (Miller, R., et al 2006).

Sensory Evaluation on Pork

There are three things to consider when conducting a sensory panel: panelist training, product presentation, and environmental conditions (Miller and Prusa, 1998). The selection process should consider individuals that have prerequisite qualifications for the specific samples being tested and no association to the study. Sample preparation should occur in a separate location to eliminate any influential error on panelist scores (e.g., cooking odors). The testing environment should have consistent lighting (i.e., shadow-free lighting, red-filtered bulbs) with minimal sound disturbance.

The variables measured in a sensory evaluation will differ based on the sample being tested but can include initial juiciness, sustained juiciness, myofibrillar tenderness, connective tissue amount, overall tenderness, flavor intensity, off-flavor intensity, texture, saltiness, smoke intensity, and bacon flavor. Each variable is measured on a continuous, 100-point scale, with indications at various values, depending on trial development. Even with the complexity of this assessment, there is still variation on determining product tenderness. To alleviate this, researchers have found other methods to evaluate the physical properties of pork products (Hansen et al., 2004; Choe et al., 2016).

Warner-Bratzler Shear Force

The Warner-Bratzler Shear Force (WBSF) test is a common estimator of meat tenderness (Ouali et al., 1995; Caine et al., 2003; Platter et al., 2003; De Huidobro et al., 2005; Destefanis et al., 2008; Choe et al., 2016) The WBSF test combines a sheer bald with crosshead speed (200-250 mm/min) to pierce the sample and measure physical tenderness (Wheeler and Koohmaraie, 1994). Samples should be uniform in their diameter (1.27 cm) and removed parallel from the longissimus muscle, using a coring device. A represented sample includes six cores that are used to calculate treatment mean but may be discarded depending on physical characteristics (e.g., connective tissue). Even though flavor and tenderness influence pork sales, product pigmentation (i.e., lightness, redness, yellowness) is also a major contributor on consumer acceptability (Hood and Mead, 1993; O'Sullivan et al., 2003).

Pork Bloom Color

During post-mortem metabolism, the oxygen supply is extinguished, causing the body to transition from using lipid stores to metabolizing muscle glycogen (Apple, 2010). Subsequently, this causes a decline in muscle pH (from 7.1-7.3 down to 5.4 to 5.7). The duration (30-60 minutes) of surface exposure of the product after harvest is crucial for “bloom” development (Brewer et al., 2001). This aerobic environment triggers “blooming”, which allows oxygen to enter the muscle tissue, turning the product red. The rate of this reaction can be measured by visual characteristics that include pale, soft, exudative (PSE), dark, firm, dry (DFD), and red, soft, exudative (RSE) (Apple, 2010). Because this observation can be inconsistently timed with measuring pork bloom color, it is common in research to use colorimetry (i.e., CIE color scale) to efficiently indicate pork color (Brewer et al., 2001). The pigmentation is calculated by the spectral curve of the sample, specifically on a scale for lightness (L^*), redness (a^*), and yellowness (b^*), respectively (Morgan et al., 1997; Čandek-Potokar et al., 2006).

Dietary Effects on Pork Quality

One of the main drivers to improving pork quality are the nutritional strategies used during the growing-finishing period. As swine producers consider increasing sustainability through the use of alternative feeding programs (i.e., including small grains), it is crucial to identify how these ingredients influence pork quality. It’s important to remember that different ingredients can impact lean muscle tissue and fat deposition differently, which both influence carcass composition (Rosenvold and Andersen, 2003). Maintaining an "ideal" AA profile (i.e., lysine) to calorie ratio is also essential in maintaining pork quality (Lebret, 2008; Lebret and Čandek-Potokar, 2022).

Because growing-finishing pigs are able to utilize various fat sources to promote their rate of gain, it is common in commercial production to include co-products such as dried distillers' grains with solubles (DDGS) to reduce diet cost, while maintaining pig performance (Apple, 2010). Historically, nutritionists have kept DDGS inclusion levels below 20% of the diet, due to the greater (10-12%) concentration of oil in DDGS (i.e., linoleic acid) (Mas et al., 2011). This recommendation was developed because feeding levels of DDGS greater than 20% caused primal cuts (i.e., bellies, loins) to contain fat that was softer and more yellow, which reduced total product value.

To promote the trade of corn processing, biofuel plants have reduced the oil content in DDGS (6-9%) to sell corn oil separately at a higher profit margin, which causes the DDGS produced to be lower in fat (Prieto et al., 2014). With this modified composition, pork producers are able to increase the inclusion rate of DDGS without impacting carcass quality.

In trials that investigated the impact of fatty acid composition from different grains on carcass quality, it was observed that pigs fed yellow and white corn produced carcasses with improved quality attributes (i.e., flavor, consumer acceptance) when compared to pigs fed a mixture of barley and yellow or white corn (Lampe et al., 2006; Sullivan et al., 2007; Baltić et al., 2011). It was also concluded that pork products from pigs fed wheat had lower WBSF scores, compared to pigs fed sorghum. Pork from pigs fed barley ranked higher for tenderness in a sensory panel than products from pigs fed barley and tricitale or corn. Inversely, the overall scores on consumer preference did not vary between pork produced from pigs fed corn, wheat, sorghum, or triticale (Lampe et al., 2006; Sullivan et al., 2007; Baltić et al., 2011). While data may support hybrid rye as an alternative ingredient in diet formulation, it's important to understand how this small grain affects pork pigmentation, texture, and consumer preference to determine the total impact on swine production and define any improvement on sustainability (Baltić et al., 2011).

To alleviate the concerns of feeding rye to pigs on pork quality, researchers have investigated the specific effects on carcass characteristics and product quality when replacing corn, barley, and wheat-based diets with hybrid rye during the growing-finishing period. When diets maintained an isocaloric and isonitrogenous profile, replacing wheat and barley with increasing levels of hybrid rye (25-50%) had no effect on HCW, yield %, or BF (Bussières, 2018). Contrary to this trial, Schwarz et al. (2014) increased the replacement rate of barley with hybrid rye (10-50%) and observed greater values for HCW and BF. Smit et al. (2019) also concluded that replacing wheat with hybrid rye (15.66-65.93%) caused no impact on carcass characteristics (HCW, yield %, BF) (Smit et al., 2019).

To verify the optimal inclusion rate of hybrid rye, Lisiak et al. (2023) determined that including 60% hybrid rye in small grain-based (wheat-barley) diets during the growing-finishing period had no impact on loin scores (i.e., smell, flavor, juiciness, or tenderness) or WBSF (Lisiak et al., 2023).

In one trial that increased the inclusion level of hybrid rye (0-100%) in corn-based diets observed no impact on HCW, yield %, BF, WBSF, bloom color or panelist scores for loin tenderness and juiciness (McGhee et al., 2021). In contrast to this, it was also determined that increasing the inclusion rate of hybrid rye caused a negative impact on pork flavor. Even though the feasibility of replacing small grains with hybrid rye may be determined, there is still an inadequate amount of data to support an optimal replacement rate of corn in a commercial setting, especially when looking at its impacts on carcass characteristics and pork quality.

Conclusion

Even though the production data may influence the producer's decision to utilize small grains in diet formulation, it is still uncertain how replacing corn with hybrid rye affects carcass characteristics and pork quality. It is important that research continues to investigate the impacts of hybrid rye on these economically important traits to determine the feeding value of hybrid rye in swine diets.

2.0 EFFECTS OF INCREASING LEVELS OF HYBRID RYE ON GROWTH PERFORMANCE AND CARCASS CHARACTERISTICS IN GROWING-FINISHING PIGS

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2.1 Abstract

A total of 2,400 barrows and gilts (FAST x PIC 800, initially 44.9 ± 8.95 kg) were used in an 89-d study to determine the effect of increasing inclusion of hybrid rye (KWS Bono) on growth performance in a commercial growing-finishing setting. Pigs were randomly allotted to 1 of 4 dietary treatments with 30 pigs per pen and 20 replications per treatment. Diets were fed over 5 phases (44.9 to 56.0, 56.0 to 69.0, 69.0 to 87.9, 87.9 to 107.5, and 107.5 to 111.6 kg respectively). Dietary treatments were corn-soybean meal-based replacing either 0, 40, 70, or 100% of the corn with hybrid rye. Diets were formulated to meet or exceed NRC 2012 recommendations for all nutrients. Pigs were weighed and feed disappearance measured to calculate ADG, ADFI, and G:F at each phase change. Pigs were marketed across three marketing events (d 68 to 89), with an equal number of pigs removed from each pen per event. Measurements were taken for carcass characteristics: yield percentage, hot carcass weight (HCW), backfat (BF) and iodine value (IV)) at the procurement facility. Two primal sections (loins and bellies) were removed from 88 pigs and sent to the Kansas State University Meat Lab Facility to conduct a sensory panel evaluation. Data was analyzed using the GLIMMIX procedure of SAS, with block as a random effect pre-planned linear and quadratic contrast statements for increasing inclusion of rye. To normalize the study, the PROC IML function of SAS was used to get coefficients

for unequal spacing of treatments. Overall (d 0 to 89), increasing the inclusion of hybrid rye from 0 to 100% decreased (linear, $P < 0.001$) average market BW, ADG, and ADFI. Because of the reduction in growth parameters, there was no difference in G:F with increasing hybrid rye inclusion, which confirms the energy value of hybrid rye used in formulation. Increasing the inclusion of hybrid rye from 0 to 100% decreased ($P < 0.001$) yield percentage, HCW, BF, and IV (P < 0.001). In summary, while there was a reduction in ADFI, ADG, market BW, yield percentage, HCW, BF, and IV, hybrid rye may be an alternative energy source to use in commercial swine production depending on economics.

Keywords: hybrid rye, growth performance, pigs

2.2 Introduction

Due to the agronomic pressure to generate biofuel, swine producers are having to compete for major ingredients (i.e., corn, soybeans) to use in diet formulation (Vonderohe et al., 2022). Along with the competition for resources, there is also an inquiry on livestock production to reform practices that promote sustainability (Mackenzie et al., 2016; Vonderohe et al., 2022). Therefore, the swine industry is investigating alternative cereals that maintain the nutritive value of their feeding programs, and how to innovate diets in a way to classify them as “sustainable”. In order to compliment sustainability with efficiency, swine producers must consider ingredients that benefit biological function, crop diversity, and reduce the amount of nutrients excreted in manure (Dourmad and Jondreville, 2007). Utilizing such a nutritional program in swine diets has the potential to enhance sustainability, along with improving profitability for all of agriculture (Honeyman, 1991; Honeyman, 1996). Promoting diversified cropping systems can improve environmental conditions by sustaining residual nutrients, reducing erosion occurrence, and enhancing the return value on common cash crops (e.g., corn, soybeans) (Sullivan, 2005). This interaction between swine and crop production is important because of the impact they both have on conserving land resources.

Although traditionally, swine diets are formulated to include a high percentage of corn, inclusion of small grains (i.e., barley, rye, triticale, wheat) can be suitable in achieving nutrient recommendations, while also reducing feed cost (Boggess et al., 2018). Depending on the source, replacing corn with small grains can maintain growth performance because of the greater concentration of amino acids (i.e., lysine, threonine, tryptophan) and available phosphorus in the small grains (Sullivan, 2005). Feeding small grains can increase the total lysine content by 30-50% and available P by 20-50% (i.e., barley, oats, triticale, wheat) (Boggess et al., 2018). Because of this potential influence on dietary nutritive value, the inclusion of small grains may have the potential to improve environmental conditions by reducing the amount of nitrogen and phosphorus lost in manure (Dourmad and Jondreville, 2007). Consequently, these small grains contain lower levels of energy, when compared to the caloric value of corn (Sullivan, 2005). Even though pigs have the capability of consuming various feedstuffs, there is insufficient data that supports commercial feeding programs that completely replace corn with small grains (Thacker and Kirkwood, 1992).

Previously, rye (*Secale cereale*) has not been considered as a feasible ingredient in swine diets because of the ergot alkaloid exposure during grain development (McGhee, 2019). To encourage small grain utilization in swine diets, a genetic company in Europe (KWS, Germany) has developed a series of rye cultivars that demonstrates superior heterosis, which accelerates the pollination stage, reducing the potential for ergot to infiltrate the stigma (Schwarz et al., 2014; Smit et al., 2019). This trait improves the plant's ability to protect itself from ergot damage and promotes grain yield (Geiger and Miedaner, 1999). Along with disease resilience, hybrid rye is also drought tolerant and can flourish in a variety of soil types, which makes this small grain important for crop diversity in the U.S. Corn Belt (Jürgens et al., 2012).

To promote hybrid rye cultivation, swine producers in Europe have begun to include this small grain in their swine rations (Schwarz et al., 2014). Even though barley is commonly used in diet formulation in Europe, it has been determined that hybrid rye is a suitable feed ingredient for pigs, because of the superior protein content and minimal fiber constituents, compared to barley. Along with improving the nutrient composition, feeding hybrid rye may also reduce diet costs associated with current corn prices (Schwarz et al., 2014; Smit et al., 2019). Even with these potential benefits, producers in the U.S. are still reluctant to feed rye to pigs, because of concerns related to ergot alkaloids in conventional rye (Bussières, 2018).

To help resolve this controversy, the current study evaluated replacing corn with hybrid rye (Bono) during the growing-finishing period of pigs and the associated effects on growth performance, carcass characteristics, and margin over feed cost (MOFC).

2.3 Materials & Methods

Growth Performance

This experiment was authorized to be conducted at a wean-to-finish facility located in Pipestone, MN 56164, USA. The barn was supervised by Pipestone Applied Research and Pipestone Nutrition. Data was collected from August 2021 to November 2021.

Animal Housing

A total of 2,400 barrows and gilts (FAST x PIC 800, 44.9 $\pm$ 8.95 kg) were utilized in an 89-d study until pigs reached a market weight of approximately 120 kg. The barn was divided into two rooms with a total of 80 test pens. Each pen contained 30 pigs with an equal number of barrows and gilts in each pen. A randomized, complete block design was used as pigs were allotted to pens on initial body weight and then blocked by location in each room. As pigs were allotted, they were randomly assigned to be fed 1 of 4 dietary treatments. All pens contained one 4-hole feeder and one cup waterer for ad libitum access to feed and water. Each diet was delivered to each specified pen by a dual-hopper, automated, feeding system (ComDel Innovation, Wahpeton, ND). The facility was curtain-sided and used a mechanical ventilation system based on target daily temperature set point. Pigs were removed from the trial, where failure to respond to veterinary treatment was observed or the health concern required removal (i.e., prolapse, severe lameness).

Dietary Treatments

Diets were provided over five phases (44.9 to 56.0, 56.0 to 69.0, 69.0 to 87.9, 87.9 to 107.5, and 107.5 to 111.6 kg, respectively) and formulated to meet or exceed all nutrient recommendations, while maintaining a constant lysine to calorie ratio (2012 NRC). Diets were corn-soybean meal based with experimental treatments replacing either 0, 40, 70, or 100% of the corn with hybrid rye. Body weight (BW) and feed disappearance were recorded at each dietary phase change (d 11, 25, 43, 61, 69, 77, and 89) to calculate average daily gain (ADG), average daily feed intake (ADFI) and the gain-to-feed ratio (G:F). With respect to concerns related to mycotoxin contamination, the hybrid rye was analyzed for the presence of 54 different mycotoxins, including ergot and its associated derivatives, and no mycotoxins were detected at the ppb or μg/kg level.

Particle Size Analysis

The particle size was evaluated for hybrid rye and corn sourced for the trial from samples that were collected during each phase change in the 89-d study. Each grain source (i.e., hybrid rye, corn) was processed in a triple roller mill prior to mixing in the designated dietary treatment. Ten samples were used in a dry, sieving method to determine the mean particle size (microns) for each grain sourced.

Carcass Characteristics

Pigs were marketed during three events, with 10 pigs removed from each pen, which equaled to a total of 800 pigs per event that were delivered to the commercial abattoir (Wholestone Farms, Fremont, NE 68025, USA) to be harvested. Pigs were anesthetized with carbon dioxide gas prior to hanging on the rail, followed by exsanguination. Each carcass was hot washed and labeled in numerical order with crayon before scanning the RFID tag to identify each carcass with the previous dietary treatment. This identification method was used to determine any effects on carcass quality by increasing the inclusion level of hybrid rye.

Characteristics measured on the rail include hot carcass weight (HCW) and backfat (BF) depth. HCW was measured after the hot wash and prior to further processing. Backfat was measured with a probe that was inserted in the midline at the 10th rib to determine the width of the subcutaneous adipose layer in each carcass. After entering the cooler, fat samples were removed from the left side belly primal of each carcass to be used for further analysis on fat quality. Each sample was labeled with the corresponding crayon number and moved to the on-site, Food Safety and Quality Assurance Lab to determine the iodine value (IV) of each belly fat sample, using a NIR Spectrometer. The yield percentage was calculated by estimating the shrinkage from each individual market weight with the corresponding HCW.

Margin Over Feed Cost

The MOFC for each diet was evaluated with four sensitivity scenarios to simulate different feed cost and hog market price conditions. The equation for MOFC [(gain x yield x $/cwt) - (feed cost/pig)] was used to determine the economics of replacing corn with hybrid rye in growing-finishing diets. Each dietary treatment was evaluated to determine MOFC in the following circumstances: high revenue/ high feed cost (HRHF), high revenue/ low feed cost (HRLF), low revenue/ high feed cost (LRHF), and low revenue/ low feed cost (LRLF). Hybrid rye was valued at 93% the value of corn to correlate to the energy value in relation to corn.

Statistical Analysis

The GLIMMIX procedure of SAS (SAS Inst., Inc. Cary, NC) was used to determine the effects of replacing corn with hybrid rye. Pen was considered as the experimental unit and blocking was the random effect. To normalize the study, the PROC IML function of SAS was used to get coefficients for unequal spacing of treatments. Pre-planned linear and quadratic contrast statements were used to test the increased inclusion of hybrid rye. Results were considered significant at a P-value $\leq$ 0.05 with any tendencies at a P-value $\leq$ 0.10.

2.4 Results

Growth Performance

During phase 1, there was a linear reduction in ADG and ADFI ($P < 0.001$) as hybrid rye increased in the diet. There tended to be a significant reduction on the G:F ratio ($P < 0.05$) as hybrid rye increased. There was no statistical difference on BW with inclusion of hybrid rye during phase 1. At the end of phase 2, ADG, ADFI, and BW decreased ($P < 0.001$) as hybrid rye increased in the diet. The G:F ratio for phase 2 was significantly ($P < 0.01$) reduced as inclusion level of hybrid rye increased. During phase 3, ADG, ADFI, and BW all significantly ($P < 0.001$) reduced, as the inclusion of hybrid rye increased. The G:F ratio was not affected by the inclusion of hybrid rye in phase 3. At phase 4, there was no statistical significance in ADG, ADFI, or the G:F ratio. There was, however, a linear ($P < 0.001$) decrease in BW as the inclusion of hybrid rye increased. In phase 5, there was a linear reduction in ADG, BW, and G:F ($P < 0.001$) as the inclusion level of hybrid rye increased. There was a tendency for ADFI to significantly reduce ($P < 0.10$) as rye increased in the diet.

Overall, increasing the inclusion level of hybrid rye resulted in a linear ($P < 0.001$) decrease in market BW. There was also a linear ($P < 0.001$) reduction in ADG and ADFI. There were no significant effects on the G:F ratio recorded (Table 2.7).

Particle Size Analysis

The mean particle size of hybrid rye (564 µm) was greater than the corn (408.7 µm) sourced for the trial (Table 2.6).

Carcass Characteristics

When hybrid rye replaced corn from 0 to 100% in the diet, there was a linear ($P < 0.001$) reduction for HCW, BF, and yield percentage when the inclusion of hybrid rye increased during the growth performance trial. A relaying impact ($P <$

0.001) was determined on the IV of the pigs fed higher levels (40-100%) of hybrid rye (Table 2.8).

Margin Over Feed Cost

In this trial, all scenarios resulted in a lower MOFC with increasing hybrid rye, with the exception of the LRHF scenario (Table 2.9).

2.5 Discussion

Because of the desire to promote sustainable swine production, the industry has begun to investigate how to utilize alternative cereals that compliment agronomic diversity and improve nutrient utilization, which both factor into diminishing the environmental footprint of swine production (Dourmad and Jondreville, 2007). With this consideration, the swine industry is also tasked to use small grains in diet formulations to decrease the reliance on corn because of the competing demand to produce ethanol (Vonderohe et al., 2022).

Hybrid rye is a major contributor to environmental sustainability because of the influence it has on recycling residual nutrients (i.e., nitrogen) and revitalizing the carbon sequestering cycle as a cover crop (Kaspar et al., 2007; Brockmueller, 2020). Growing hybrid rye can reduce nitrogen loss in the field by 93%, which improves cash crop (i.e., corn, soybeans) biomass and reduces carbon emissions (Miedaner et al., 2018). Hybrid rye can also grow in soils that have limited access to water and nutrients, which makes this a suitable cover crop for the U.S. Corn Belt (Jürgens et al., 2012; Hübner et al., 2013). These characteristics factor into why hybrid rye is being investigated as an alternative ingredient in commercial swine diets.

In this effort, we hypothesized that the direct replacement of corn with increasing levels (0-100%) of hybrid rye during the growing-finishing stage would impact growth performance, carcass characteristics, and MOFC in a commercial setting.

When evaluating the nutrient profile of hybrid rye, the percentage of total lysine was 0.41%, compared to corn at 0.28% (McGhee, 2019). In terms of metabolizable energy (ME), hybrid rye was reported at 3153 kcal/kg, compared to corn at 3274 kcal/kg. Because there are limited studies characterizing the nutrient profile of hybrid rye, the energy content of the dietary treatments was not adjusted as rye replaced corn. Thus it was expected that pigs fed hybrid rye would increase their daily consumption to compensate for the 3.5% reduction in ME content (Sullivan, 2005; McGhee, 2019), but that was not the case.

The linear reduction in ADFI as hybrid rye increased in the diet, may reflect a satiety effect of hybrid rye or the particle size differences between hybrid rye and corn. Arabinoxylans contribute approximately 47% of the fiber constituents in hybrid rye (Antoniou et al., 1981; Bengtsson and Åman, 1990; Allen, 2002; Jürgens et al., 2012). This non-starch polysaccharide intensifies the association with water, which increases viscosity in the gastrointestinal tract. This reaction delays the host’s ability to absorb nutrients and prolongs satiation (Antoniou et al., 1981; Jürgens et al., 2012). The lack of difference in G:F suggests that the lower ADG in pigs fed hybrid rye-based diets is related to the decreased ADFI, rather than an altered metabolic response and supports previous work indicating that hybrid rye has a relatively high energy value (93%) compared to the caloric content of corn (McGhee, 2019). Subsequently, if the energy profile of the hybrid rye diets had been adjusted as inclusion increased to be equivalent to the corn control diet, it is expected that a similar rate of gain would have been observed.

The decrease in ADFI may have also caused a reduction in lysine consumption because dietary treatments were only formulated to maintain a lysine to calorie ratio. Even though all AA requirements were met based on the 2012 NRC recommendations, diets were not supplemented with added crystalline AA to maintain the same profile across treatments. This theory could contribute to why there was an overall reduction in pig performance.

Previous research has determined that if hybrid rye-based diets are formulated to maintain energy content and amino acid ratios, that there is no impact on pig performance. Increasing the inclusion level of hybrid rye (25-50%), while maintaining an isocaloric and isonitrogenous profile of wheat and barley control diets, had no impact on ADG, ADFI, or G:F during a four-phase feeding program (Bussières, 2018). There was also no associated reduction on HCW, yield percentage, or BF. Similar to this observation, a trial that increased the replacement rate of barley with hybrid rye from 10 to 50%, observed greater carcass value in the pigs that were fed higher levels of hybrid rye (Schwarz et al., 2014). Another study that replaced wheat with hybrid rye (15.66-65.93%) observed no differences on carcass characteristics (HCW, yield percentage, BF) (Smit et al., 2019).

This work would explain why there was an impact on pig performance (ADG, ADFI) and a subsequent reduction on carcass characteristics (HCW), as diets were only isonitrogenous and not isocaloric. The growth performance in the current study could also contribute to why there was a decrease recorded on BF as hybrid rye increased in the diet. It has been observed in pervious literature that restricting energy consumption causes a subsequent increase in carcass leanness and reduction in fat deposition (Pettigrew and Esnaola, 2001; Benz et al., 2011). Since dietary fat was not included to maintain caloric value across treatments, the decline in voluntary feed intake in pigs fed higher levels of hybrid rye (40-100%) may reflect the reduction in BF.

The reduction in yield % in the current study could be due to the greater concentration of neutral detergent fiber (15.16%) in rye than corn (10.11%) (McGhee, 2019), along with the fact that there were no adjustments made on rye inclusion as pigs entered the finishing period. It has been noted in literature that if fiber ingredients (i.e., DDGS) are fed through the duration of the finishing period, that the physiochemical properties of the fiber sourced can alter the pig's ability to efficiently digest and metabolize nutrients (Wenk, 2001). This reaction causes an influx in rate of passage to digest the fiber, which causes cell proliferation (i.e., greater visceral organ mass) and a decline on yield % (Gill et al., 2000; Nemechek et al., 2015; Coble et al., 2018). Salyer et al. (2012) reported that an inclusion level of 30% DDGS during the finishing period caused a reduction on carcass yield. It was comparable that feeding 20% wheat midds during the finishing stage resulted in a decrease on yield % (Salyer et al., 2012).

To alleviate this impact on carcass yield, it has been reported that if high-fiber ingredients (i.e.., DDGS, what midds) are withdrawn from the diet approximately 3 weeks before slaughter that there is no impact on performance (Coble et al., 2018). To address the current study, it is suggested that if diets would have been adjusted to include less hybrid rye (> 40%) as pigs enter the finishing stage, that yield % would have been similar across dietary treatments.

The reduction observed on IV in the current study may reflect the greater concentration of unsaturated fat in corn-based diets compared to the diets with increasing levels of hybrid rye (40-100%). Rentfrow et al. (2003) determined that feeding conventional, corn-based (86.25%) diets with a proportion of steric (12.63%) and linoleic acid (9.05%) does not impact on belly firmness. When comparing the fatty acid profile of hybrid rye-based diets (67.45%), McGhee et al. (2021) reported a lower proportion of steric acid (4.01% ± -0.40) and higher amount of linoleic acid (45.13% ± -3.14) in the small grain. Even though there is a greater percentage of unsaturated fat (i.e., linoleic acid) in hybrid rye than corn, the total amount of ether extract is substantially lower in rye (Bono) (1.24%) than corn (3.61%) (McGhee, 2019), which would infer that reduction in unsaturation (i.e., lower IV) in the pigs fed greater levels of hybrid rye.

The economics of replacing corn with hybrid rye (0-100%) in swine diets in a commercial setting was based on four scenarios which considered when hog prices were benchmarked as high versus low and corn prices were high versus low. When hog prices were high and corn prices were either high or low, increasing the level of hybrid rye in the diet caused a significant reduction ($1.60-4.55/ pig) on MOFC. However, when corn prices remained high and hog prices reduced, MOFC increased $1.01/ pig when the replacement rate of hybrid rye for corn increased from 0 to 100%.

The differences in MOFC are likely related to the impact on growth performance and subsequently, carcass characteristics in the pigs fed higher levels of hybrid rye. Because hog prices are estimated on HCW rather than live BW, it is indicative that growing-finishing diets that supplement hybrid rye should not exceed a replacement rate of corn by 40%.

It’s suggested that if the rye-based diets (40%, 70%, 100%) were formulated to be isocaloric and isonitrogenous across treatments, there would have been no impact on pig performance. Contrary to this, adding fat to the diet can increase feed cost, which leads to a reduction in MOFC. There is also constraint on the percentage of fat to include because of the potential impact on IV. With the results from this study, we can indicate that the optimal inclusion level of hybrid rye should not exceed 40%, until further investigation is made on alternative approaches to improve pig performance and carcass value.

Conclusion

In conclusion, this study reveals that exceeding a 40% replacement rate of corn with hybrid during the growing-finishing phase will lead to detrimental effects on growth performance, carcass characteristics, and MOFC. Because of the various alternatives to why there was a reduction in pig performance, it is not verified that reformulating diets with increasing the inclusion of hybrid rye would sustain pig performance or profitability. Further investigation should be conducted on supplementing additional sources to maintain the caloric value and amino acid profile of corn-based diets to clarify the feeding value of hybrid rye in swine diets in a commercial setting.

Table 2.1 Composition of growing-finishing diet (Phase 1)

	Hybrid Rye Replacing Corn[1], %			
Ingredient, %	0	40	70	100
Corn (Ground)	75.62	45.35	22.68	0.00
Hybrid Rye (KWS)	0.00	30.24	52.93	75.61
Soybean Meal	21.85	21.90	21.85	21.85
Limestone	0.85	0.83	0.83	0.80
Salt	0.50	0.50	0.50	0.50
Lysine HCl	0.40	0.36	0.32	0.29
Monocalcium Phosphate 21%	0.36	0.41	0.45	0.49
PGF VTM[2]	0.10	0.10	0.10	0.10
L-Threonine	0.13	0.12	0.11	0.11
Phytase[3]	0.04	0.04	0.04	0.04
Tri-basic Copper Chloride	0.03	0.03	0.03	0.03
L-Tryptophan	0.02	0.01	0.01	0.00
DL- Methionine - 99%	0.09	0.13	0.17	0.20
L-Valine	0.02	0.01	0.00	0.00
Nutrient Analysis				
ME, kcal/kg	3232	3158	3102	3047
CP, %	16.76	16.94	17.03	17.15
Calcium, %	0.58	0.58	0.59	0.59
Phosphorus, %	0.43	0.44	0.44	0.45
Phosphorus - STTD	0.38	0.36	0.35	0.33
Phosphorus - Avail	0.29	0.29	0.29	0.29
Ca:AvP	2.01	2.01	2.04	2.03
SID Lysine, %	1.04	1.02	1.00	0.99
SID Lys:ME	3.22	3.23	3.23	3.23
SID M+C:Lys	58	58	58	58
SID Thr:Lys	63	63	63	63
SID Trp:Lys	19	19	19	20
SID Ile:Lys	59	60	61	63
SID Val:Lys	67	67	67	69
SID Leu:Lys	129	119	112	105

[1]Replaced corn with hybrid rye inclusion at a rate of 0, 40, 70, and 100.

[2]PGF VTM = Pipestone grow-finish vitamin trace mineral (amt/ kg diet).

[3]Quantum blue, 200 FTU/kg of phytase (AbVista).

Table 2.2 Composition of growing-finishing diet (Phase 2)

	Hybrid Rye Replacing Corn[1], %			
Ingredient, %	0	40	70	100
Corn (Ground)	79.46	47.66	23.84	0.00
Hybrid Rye (KWS)	0.00	31.78	55.61	79.45
Soybean Meal	18.25	18.25	18.20	18.20
Limestone	0.80	0.78	0.78	0.75
Salt	0.50	0.50	0.50	0.50
Lysine HCl	0.36	0.31	0.28	0.24
Monocalcium Phosphate 21%	0.31	0.37	0.43	0.45
PGF VTM[2]	0.10	0.10	0.10	0.10
L-Threonine	0.10	0.10	0.09	0.09
Phytase[3]	0.04	0.04	0.04	0.04
Tri-basic Copper Chloride	0.03	0.03	0.03	0.03
L-Tryptophan	0.02	0.01	0.00	0.00
DL- Methionine - 99%	0.05	0.10	0.13	0.17
L-Valine	0.00	0.00	0.00	0.00
Nutrient Analysis				
ME, kcal/kg	3252	3175	3115	3058
CP, %	15.34	15.50	15.60	15.73
Calcium, %	0.55	0.55	0.56	0.55
Phosphorus, %	0.40	0.41	0.42	0.43
Phosphorus - STTD	0.36	0.34	0.33	0.31
Phosphorus - Avail	0.28	0.28	0.28	0.28
Ca:AvP	1.98	1.99	2.00	2.00
SID Lysine, %	0.92	0.90	0.88	0.86
SID Lys:ME	2.83	2.83	2.82	2.82
SID M+C:Lys	58	58	58	58
SID Thr:Lys	64	64	64	64
SID Trp:Lys	19	19	19	20
SID Ile:Lys	60	62	63	64
SID Val:Lys	67	69	70	72
SID Leu:Lys	137	125	117	108

[1]Replaced corn with hybrid rye inclusion at a rate of 0, 40, 70, and 100.

[2]PGF VTM = Pipestone grow-finish vitamin trace mineral (amt/ kg diet).

[3]Quantum blue, 200 FTU/kg of phytase (AbVista).

Table 2.3 Composition of growing-finishing diet (Phase 3)

	Hybrid Rye Replacing Corn[1], %			
Ingredient, %	0	40	70	100
Corn (Ground)	84.11	50.49	25.24	0.00
Hybrid Rye (KWS)	0.00	33.65	58.89	84.11
Soybean Meal	13.65	13.60	13.60	13.60
Limestone	0.80	0.78	0.75	0.73
Salt	0.50	0.50	0.50	0.50
Lysine HCl	0.37	0.32	0.29	0.26
Monocalcium Phosphate 21%	0.27	0.33	0.37	0.41
PGF VTM[2]	0.10	0.10	0.10	0.10
L-Threonine	0.10	0.09	0.09	0.09
Phytase[3]	0.04	0.04	0.04	0.04
Tri-basic Copper Chloride	0.03	0.03	0.03	0.03
L-Tryptophan	0.03	0.01	0.01	0.00
DL- Methionine - 99%	0.03	0.08	0.12	0.16
L-Valine	0.00	0.00	0.00	0.00
Nutrient Analysis				
ME, kcal/kg	3277	3195	3134	3072
CP, %	13.54	13.68	13.82	13.95
Calcium, %	0.52	0.53	0.52	0.52
Phosphorus, %	0.37	0.38	0.39	0.40
Phosphorus - STTD	0.34	0.32	0.30	0.29
Phosphorus - Avail	0.26	0.26	0.26	0.26
Ca:AvP	2.01	2.02	2.01	2.00
SID Lysine, %	0.82	0.79	0.78	0.77
SID Lys:ME	2.49	2.48	2.48	2.48
SID M+C:Lys	58	58	58	58
SID Thr:Lys	64	64	64	64
SID Trp:Lys	19	19	19	19
SID Ile:Lys	58	60	62	63
SID Val:Lys	67	69	70	71
SID Leu:Lys	141	127	117	105

[1]Replaced corn with hybrid rye inclusion at a rate of 0, 40, 70, and 100.

[2]PGF VTM = Pipestone grow-finish vitamin trace mineral (amt/ kg diet).

[3]Quantum blue, 200 FTU/kg of phytase (AbVista).

Table 2.4 Composition of growing-finishing diet (Phase 4)

	Hybrid Rye Replacing Corn[1], %			
Ingredient, %	0	40	70	100
Corn (Ground)	86.56	51.95	25.98	0.00
Hybrid Rye (KWS)	0.00	34.63	60.59	86.59
Soybean Meal	11.35	11.30	11.30	11.25
Limestone	0.75	0.73	0.70	0.68
Salt	0.50	0.50	0.50	0.50
Lysine HCl	0.36	0.32	0.29	0.26
Monocalcium Phosphate 21%	0.19	0.25	0.29	0.34
PGF VTM[2]	0.10	0.10	0.10	0.10
L-Threonine	0.10	0.10	0.09	0.09
Phytase[3]	0.04	0.04	0.04	0.04
Tri-basic Copper Chloride	0.03	0.03	0.03	0.03
L-Tryptophan	0.03	0.02	0.01	0.00
DL- Methionine - 99%	0.01	0.07	0.11	0.15
L-Valine	0.00	0.00	0.00	0.00
Nutrient Analysis				
ME, kcal/kg	3293	3209	3145	3082
CP, %	12.64	12.80	12.93	13.05
Calcium, %	0.48	0.48	0.48	0.48
Phosphorus, %	0.34	0.36	0.37	0.37
Phosphorus - STTD	0.32	0.30	0.28	0.27
Phosphorus - Avail	0.24	0.24	0.24	0.24
Ca:AvP	2.01	2.02	2.01	2.01
SID Lysine, %	0.76	0.74	0.72	0.71
SID Lys:ME	2.29	2.28	2.29	2.29
SID M+C:Lys	58	58	58	58
SID Thr:Lys	65	65	65	65
SID Trp:Lys	19	19	19	19
SID Ile:Lys	58	60	61	62
SID Val:Lys	67	69	70	71
SID Leu:Lys	145	130	117	104

[1]Replaced corn with hybrid rye inclusion at a rate of 0, 40, 70, and 100.

[2]PGF VTM = Pipestone grow-finish vitamin trace mineral (amt/ kg diet).

[3]Quantum blue, 200 FTU/kg of phytase (AbVista).

Table 2.5 Composition of growing-finishing diet (Phase 5)

	Hybrid Rye Replacing Corn[1], %			
Ingredient, %	0	40	70	100
Corn (Ground)	88.20	52.90	26.46	0.00
Hybrid Rye (KWS)	0.00	35.28	61.74	88.19
Soybean Meal	9.80	9.80	9.75	9.75
Limestone	0.75	0.73	0.70	0.68
Salt	0.50	0.50	0.50	0.50
Lysine HCl	0.31	0.27	0.24	0.20
Monocalcium Phosphate 21%	0.20	0.26	0.31	0.35
PGF VTM[2]	0.10	0.10	0.10	0.10
L-Threonine	0.08	0.07	0.07	0.07
Phytase[3]	0.04	0.04	0.04	0.04
Tri-basic Copper Chloride	0.03	0.03	0.03	0.03
L-Tryptophan	0.02	0.01	0.00	0.00
DL- Methionine - 99%	0.00	0.04	0.08	0.12
L-Valine	0.00	0.00	0.00	0.00
Nutrient Analysis				
ME, kcal/kg	3299	3213	3148	3084
CP, %	12.01	12.19	12.31	12.46
Calcium, %	0.48	0.48	0.48	0.48
Phosphorus, %	0.34	0.35	0.36	0.37
Phosphorus - STTD	0.32	0.30	0.28	0.27
Phosphorus - Avail	0.24	0.24	0.24	0.24
Ca:AvP	2.00	2.00	1.99	2.00
SID Lysine, %	0.68	0.66	0.65	0.63
SID Lys:ME	2.04	2.05	2.05	2.04
SID M+C:Lys	61	58	58	58
SID Thr:Lys	66	66	65	66
SID Trp:Lys	19	19	19	20
SID Ile:Lys	61	63	64	66
SID Val:Lys	72	73	74	76
SID Leu:Lys	157	139	125	111

[1]Replaced corn with hybrid rye inclusion at a rate of 0, 40, 70, and 100.

[2]PGF VTM = Pipestone grow-finish vitamin trace mineral (amt/ kg diet).

[3]Quantum blue, 200 FTU/kg of phytase (AbVista).

Table 2.6 Particle size of hybrid rye and corn sourced in growing-finishing diets[1]

Items[2]	Mean Particle Size Diameter, µm[3]
Corn	408.7
Hybrid Rye	564

[1]A triple roller hammer mill was used to process hybrid rye and corn sourced for the 89-d study.
[2]Each grain sample was collected prior to being included in dietary treatments.
[3]Particle size was calculated using 10 total samples for each grain sourced.

Table 2.7 Effects of increasing hybrid rye on growth performance in growing-finishing pigs[1]

	Hybrid Rye Replacing Corn[2], %					*P*-Values	
Items[3]	0	40	70	100	SEM	Linear	Quadratic
Initial BW	44.9	44.8	44.8	44.9	0.72	0.902	0.837
Wk 1							
BW	56.3	56.2	55.9	55.6	0.71	0.148	0.745
ADG	1.04	1.04	1.01	0.98	0.01	0.001	0.046
ADFI	1.96	1.94	1.81	1.78	0.03	0.001	0.445
G:F	0.529	0.535	0.562	0.549	0.01	0.015	0.402
Wk 2							
BW	70.1	69.5	68.8	67.6	0.75	0.001	0.295
ADG	0.98	0.94	0.91	0.85	0.02	0.001	0.359
ADFI	2.27	2.18	2.14	2.07	0.03	0.001	0.897
G:F	0.433	0.430	0.425	0.411	0.01	0.003	0.195
Wk 3							
BW	89.7	88.4	87.6	85.8	0.89	0.001	0.394
ADG	1.08	1.04	1.03	1.01	0.02	0.000	0.516
ADFI	2.80	2.73	2.68	2.66	0.06	0.001	0.589
G:F	0.387	0.382	0.387	0.383	0.01	0.641	0.749
Wk 4							
BW	109.2	107.5	107.3	105.4	1.03	0.001	0.669
ADG	1.07	1.05	1.09	1.08	0.02	0.241	0.433
ADFI	2.91	2.88	2.92	2.92	0.04	0.539	0.465
G:F	0.368	0.364	0.374	0.371	0.00	0.275	0.670
Wk 5							
BW	114.0	111.6	112.0	108.9	1.16	0.001	0.468
ADG	1.03	0.99	0.99	0.90	0.03	0.001	0.239
ADFI	2.86	2.93	2.92	2.74	0.09	0.066	0.003
G:F	0.362	0.340	0.339	0.331	0.01	0.001	0.334
Overall							
BW[4]	126.0	123.9	123.1	120.8	1.03	0.001	0.577
ADG	1.05	1.02	1.01	0.98	0.01	0.001	0.750
ADFI	2.70	2.66	2.62	2.58	0.03	0.001	0.953
G:F	0.387	0.384	0.387	0.382	0.01	0.177	0.625

[1]A total of 2,400 pigs were used with 20 replicates per treatment.
[2]Replaced corn with hybrid rye inclusion at a rate of 0, 40, 70, and 100%.
[3]ADG = average daily gain, ADFI = average daily feed intake, G:F = gain to feed ratio, BW = body weight.
[4]Pens were marketed by removing the largest 10 pigs per pen on d 68, 76, and 89.

Table 2.8 Effects of increasing hybrid rye inclusion on carcass characteristics in growing-finishing pigs[1]

	Hybrid Rye Replacing Corn[2], %					*P*-Values	
Items	0	40	70	100	SEM	Linear	Quadratic
Market BW, kg[3]	126.0	123.9	123.2	120.8	1.03	0.001	0.578
Yield, %	73.4	72.8	72.6	72.1	0.00	0.001	0.527
HCW, kg	88.0	85.9	85.2	82.6	2.01	0.001	0.293
Backfat, cm	2.57	2.46	2.39	2.39	0.02	0.001	0.297
Iodine Value[4]	67.0	65.4	64.8	63.6	0.27	0.001	0.648

[1]A total of 2,400 pigs were used in an 89-d study.
[2]Replaced corn with hybrid rye inclusion at a rate of 0, 40, 70, and 100%.
[3]Pens were marketed in three events on d 68, 76, and 89. Ten pigs were removed from each pen with a total of 800 pigs removed per event.
[4]During each marketing event, two barrows per pen were used to collect belly samples for IV analysis.

Table 2.9 Effects of increasing hybrid rye inclusion on margin over feed cost in growing-finishing pigs[1]

	Hybrid Rye Replacing Corn[2], %					*P*-values	
Items[3]	0	40	70	100	SEM	Linear	Quadratic
HRHF	56.74	55.50	56.07	54.81	1.17	0.060	0.977
HRLF	81.59	79.13	78.89	77.04	1.05	0.001	0.803
LRHF	10.56	10.87	11.90	11.57	0.84	0.025	0.595
LRLF	35.40	34.50	34.72	33.80	0.71	0.009	0.928

[1]MOFC was estimated using benchmarked prices for hogs on a carcass basis and feed cost associated with replacing corn with hybrid rye from 0-100% for the duration of the 89-d study.
[2]Replaced corn with hybrid rye inclusion at a rate of 0, 40, 70 and 100%.
[3]HRHF = high revenue/ high feed cost, HRLF = high revenue/ low feed cost, LRHF = low revenue/ high feed cost, LRLF = low revenue/ low feed cost.

3.0 THE EFFECTS OF INCREASING HYBRID RYE IN GROWING-FINISHING PIGS ON PORK QUALITY ATTRIBUTES

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3.1 Abstract

Increasing inclusion of hybrid rye (Bono) in growing-finishing pig diets was evaluated to determine the effects on product sensory evaluation, Warner-Bratzler shear force (WBSF), and chop bloom analysis. A total of 2,400 barrows and gilts (FAST x PIC 800, initially 44.9 kg) were assigned to a five-phase (44.9 to 56.0, 56.0 to 69.0, 69.0 to 87.9, 87.9 to 107.5, and 107.5 to 111.6 kg respectively) feeding program and randomly allotted to 1 of 4 dietary treatments. Diets were corn-soybean based with hybrid rye replacing 0, 40, 70, or 100% of the corn. All diets were formulated to meet or exceed NRC (2012) recommendations for all nutrients. Pigs were marketed in three events from d 69-89, with pigs from the second marketing event designated to provide samples for pork quality assessments. Two primal sections (loins and bellies) were removed from 88 pigs and sent to the KSU Meat Lab Facility to conduct a sensory panel evaluation. A WBSF test and chop bloom analysis was conducted at the same location. Data was analyzed using the GLIMMIX procedure of SAS, with block as a random effect and pre-planned linear and quadratic contrast statements to test hybrid rye inclusion. Sensory chop measures for initial juiciness, sustained juiciness, myofibrillar tenderness, and overall tenderness decreased ($P < 0.05$) with increasing levels of hybrid rye. Connective tissue amount, pork-flavor intensity, and off-flavor intensity were not affected by dietary treatment. All belly measures including texture, saltiness, smoke intensity, bacon flavor, and off flavor were

not affected by increasing the inclusion of hybrid rye. The WBSF scores increased ($P < 0.05$) as hybrid rye increased in the diet. There was a linear and quadratic ($P < 0.05$) increase in chop bloom color b* (yellowness) and a tendency for a* (redness) to increase as rye inclusion increased. Peak a* and b* were noted at a 70% replacement rate of corn with hybrid rye. Both a* and b* resulted in a quadratic response as the replacement rate of corn with hybrid rye reached 70%. In summary, while there was a reduction in chop product attributes for tenderness and WBSF, the reduction is smaller than what the average consumer is likely to detect. The peak response on a* and b* concludes that the replacement rate of corn with hybrid rye should not exceed 70% in growing-finishing diets to eliminate any impact on loin color. Because there was no effect on bacon quality, replacing corn with hybrid rye in growing-finishing pig diets from 0-100% would not impact pork quality attributes related to consumer purchasing decisions for bacon products.

Keywords: hybrid rye, growing-finishing pigs, pork quality attributes

3.2 Introduction

As the impact of animal agriculture on environmental conditions continues to be more scrutinized, it is imperative that pork producers utilize alternative techniques in production that promote land conservation. Along with sustaining environmental conditions, producers are urged to utilize feeding programs that reduce the amount of nutrients (i.e., nitrogen, phosphorus) excreted into the atmosphere because of the total impact on sustainability metrics (Vonderohe et al., 2022). Even though the U.S. swine industry has reduced a third of their environmental footprint on each unit of pork produced, there is still a significant impact from total swine production. This is due to the growing population and subsequent pressure for the food animal industry to meet per capita consumption rates. The total impact of swine production on environmental conditions is also significant related to the detriment (50-60%) of propagating feed ingredients (i.e., corn, soybeans) for traditional swine diets. To alleviate these constraints on sustainability, producers are advised to promote localized agriculture, specifically growers that incorporate small cereals (e.g., barley, triticale, rye) in their cropping systems.

Even with supporting environmental sustainability, producers are still concerned of the subsequent impact that small grain-based diets may have on product quality attributes related to consumer purchasing decisions. Influences on pH, color, texture, and intramuscular fat are all related to consumer acceptability of pork products. Understanding the eating experience of pork produced from pigs fed small grains is crucial in complimenting all aspects of sustainability for the swine industry.

Because growing-finishing pigs are able to utilize various fat sources to promote their rate of gain, it is common in commercial production to include co-products such as dried distillers' grains with solubles (DDGS) to reduce diet cost while maintaining pig performance (Apple, 2010). Previously, if diets exceeded the recommended rate of DDGS (≤ 20%), there was a major impact on carcass fabrication, due to the greater (10-12%) concentration of unsaturated fat (i.e., linoleic acid) (Mas et al., 2011). Inclusion rates above this caveat would cause primal cuts (i.e., bellies, loins) to contain fat that was softer and more yellow, which reduced total product value. To promote the trade of corn processing, biofuel plants have reduced the oil content in DDGS (6-9%) to sell corn oil separately at a higher profit margin, which causes the DDGS produced to be lower in fat (Prieto et al., 2014). Subsequently, this improvement on fatty acid profile in DDGS becomes controversial for environmental and economical sustainability, because of the reduced caloric value as a feed ingredient (i.e., oil extracted decreases energy content) and constraint on environmental conditions to transport DDGS needed for diet formulation.

In a study assessing the effects of small grain-based diets in a commercial setting, it was observed that pigs fed yellow and white corn, yielded carcasses with greater quality attributes (i.e., flavor, consumer acceptance) than pigs fed a mixture of barley and yellow or white corn (Lampe et al., 2006; Sullivan et al., 2007; Baltić et al., 2011). It was also concluded that pork products from pigs fed wheat had lower WBSF scores, compared to pigs fed sorghum. Pork from pigs fed barley ranked higher for tenderness in a sensory panel than products from pigs fed barley and tricitale or corn. Alternatively, the overall scores on consumer preference didn't not vary between pork produced from pigs fed corn, wheat, sorghum, or triticale (Lampe et al., 2006; Sullivan et al., 2007; Baltić et al., 2011).

While hybrid rye has been noted to improve environmental conditions (i.e., cover crop application) in crop production, it's important to understand how this small grain affects pork pigmentation, texture, and consumer preference to determine the total impact on sustainable swine production (Baltić et al., 2011). To investigate this, the current study evaluated the effects of increasing replacement rate of corn with hybrid rye (0-100%) during the growing-finishing period on pork quality attributes using a trained, sensory evaluation, WBSF, and bloom color analysis. Our hypothesis was that increasing the inclusion of hybrid rye would negatively impact pork quality.

3.3 Materials & Methods

The dietary treatments of pigs selected for meat quality analysis were described in Chapter 2 (Section 2.3 and 2.4, respectively). This study was approved by the Kansas State

University (KSU) Institutional Review Board for all procedures of human subjects to participate in the product sensory evaluation (IRB #7440.7, Feb. 02, 2021).

Pork Chop Sample Preparation

Eighty-eight center-cut pork loins (IMPS #413) representing the four treatments were received from SDSU. At 12-h post arrival, loins were sorted by treatment labeled A through D and held for 5 days at 0 – 4°C prior to fabrication.

Loins were cut into 2.5 cm thick chops using a manual cutting guide (DK-150, G-R Manufacturing, Manhattan, KS) and chops from the approximate center of the loin, anterior to the *gluteus medius* were assigned for color analysis, trained sensory evaluation and WBSF evaluation. Immediately following cutting, designated chops were individually vacuum packaged using a commercial vacuum packager. Chops were frozen (-20°C) until further evaluation.

Chop Trained Sensory Evaluation

Chops selected for trained sensory analysis were thawed at 2 to 4°C for 24-h prior to cooking. Samples were prepared to 71°C using a clamshell style grill (Cuisinart Griddler Deluxe, East Windsor, NJ) and temperature was monitored using a probe thermometer (Thermapen Mk4, ThermoWorks, American Fork, UT). The chops were then cut into 2.5-cm thick × 1-cm × 1-cm cuboids, and two cuboid samples were served to each panelist.

Sensory panelists were trained according to the American Meat Science Association (AMSA) sensory guidelines (AMSA, 2015). Eleven panels were conducted at the Kansas State University Meat Science Sensory Lab. For each panel, eight panelists were placed in individual booths under low-intensity red incandescent light. Panelists were provided with nine samples, including a warm-up sample that was discussed for calibration prior to the eight tested samples. Panelists evaluated each sample for initial juiciness, sustained juiciness, myofibrillar tenderness, connective tissue amount, overall tenderness, pork flavor intensity, off-flavor intensity, and an allowed off-flavor description if necessary. Traits were measured on a continuous 100-point line scale with descriptive anchors at 0, 50, and 100. The descriptive anchor of 0 correlated with extremely dry/tough/bland/none; 50 neither dry nor juicy/neither tough nor tender; and 100 extremely juicy/tender/abundant/extremely intense.

Panelist responses were recorded on a digital survey (Qualtrics Software, Provo, UT) using electronic tablets (Hewlett-Packard, Palo Alto, CA). Furthermore, peak temperatures were recorded.

Warner-Bratzler Shear Force

A Warner-Bratzler shear force analysis was performed using the protocol described by the AMSA Meat Cookery and Sensory Guidelines (AMSA, 2016). All samples were thawed at 2 to 4°C for 24 hours prior to cooking preparation. A total of 6 cores (1.27-cm diameter) were cut from each cooked chop parallel to the muscle fiber orientation. The cores were then sheared perpendicular to the longissimus muscle fiber, using an Instron testing machine (model 5569, Instron Corp., Canton, MA) with a crosshead speed of 250 mm/min and a load cell of 100 kg. The measurements of 6 cores were collected per chop and averaged to record peak force (kg).

Chop Bloom Color Analysis

Following a 50-day freeze period, chops designated for color analysis were thawed at 2 to 4°C for 24 hours prior to data collection. Fifteen samples per treatment representing different loins were used for color analysis. L*, a*, and b* data was collected using a

Hunter Lab Miniscan spectrophotometer (Illuminant A, 2.54-cm aperture, 10° observer, Hunter Lab Associates Laboratory, Reston, VA) at three locations within the chop and averaged following a 30-minute bloom time. Color was described using a three-dimensional coordinate system.

Bacon Sample Preparation

Eighty-eight, fresh pork bellies (IMPS #409) representing four treatments were received from SDSU. After 12 hours post arrival, bellies were sorted by treatment labels A through D and individually vacuum-packaged. All treatments were held for 5 days at 0 – 4°C prior to fabrication.

Bellies were processed in order from A (control) to D (100% inclusion) to prevent cross-contamination between treatments. All bellies were injected to 12% of green weight with a brine solution consisting of 86.8% water, 11.8% modern cure (Holly Quick Cure, Excalibur, Pekin, IL, U.S.A.), 0.68% sodium erythorbate (0700139-V, Excalibur, Pekin, IL, U.S.A.), 0.39% salt, and 0.31% sugar. Immediately following the injection, bellies tumbled on a 2-hour schedule. Weights were collected prior to injection, post-injection, and following the tumbling schedule to ensure 10% brine retainment. Once retainment was ensured, bellies were put into a single truck smokehouse (D7752 Mauer Inc., Reichenau, Germany) for smoking/cooking. A standard thermal processing schedule was utilized and included: stage one with smokehouse setting of 57°C dry bulb and 30°C wet bulb for 30 minutes; stage two consisted of 54°C dry bulb, 44°C wet bulb, and natural smoke applied for 30 minutes; stage three was 54°C dry bulb and 35°C wet bulb for 150 minutes; stage four was 57°C dry bulb and 30°C for wet bulb for 130 minutes to reach an internal belly temperature of at least 54°C.

Cooked bellies were placed into a chiller (2 ± 1°C) for 12 hours. After cooling, chilled weights were collected. Each belly was sliced 1.5 mm thick with a horizontal slicer (Model Puma 700 F, Treif, Oberlahr, Germany) from the anterior to posterior end. Nine slices were collected from the approximate center of each belly for trained sensory analysis. Immediately following slicing, slices were vacuum packaged using a commercial vacuum packager. Bacon samples were frozen (-20°C) until further evaluation.

Bacon Trained Sensory Evaluation

Bacon samples selected for trained sensory analysis were thawed at 2 to 4°C for 24 hours prior to cooking. Sensory samples were placed on wire cooking racks in a Blodgett dual-flow, forced-air oven (DFD-201, G.S. Blodgett Co., Inc., Burlington, VT, U.S.A.) to cook at 176.7 °C for five minutes while rotating the pans 180° halfway through the cooking process. After cooking, slices were blotted with paper towels to remove excess grease as described by Lowe et al. (2014). Slices were cut to a uniform 6-inch sample length.

Trained sensory panelists were trained according to the AMSA sensory guidelines (AMSA, 2015). Eleven panels were conducted at the Kansas State University Meat Science Sensory Lab. For each panel, eight panelists were placed in individual booths under low-intensity red incandescent lights. Panelists were fed nine samples, including a warm-up sample that was discussed for calibration prior to the eight tested samples. Panelists evaluated each sample for saltiness, smoke intensity, bacon flavor, oxidized flavor, and other off flavors. Traits were measured on a continuous 100-point line scale with descriptive anchors at 0 and 100. The descriptive anchor of 0 correlated with not salty/not smoky/bland/none and 100 extremely salty/smoky/intense/extremely intense. Panelist responses were recorded on a digital survey (Qualtrics Software, Provo, UT) using electronic tablets (Hewlett-Packard, Palo Alto, CA).

Statistical Analysis

The GLIMMIX procedure of SAS (SAS Inst., Inc. Cary, NC) was used to determine the effects of replacing corn with hybrid rye. The model used for bacon and chop sensory analysis included the fixed effect of rye inclusion level and the random effect of panel session. For WBSF data, peak cooked temperature was included in the model as a covariate. The model used for the color data included only the fixed effect of treatment. Results were considered significant at a $P \leq 0.05$ with any tendencies that are at a $P < 0.10$.

3.4 Results

Chop Trained Sensory Evaluation

As inclusion level of hybrid rye increased in the diet during the growing-finishing phase there was a linear ($P < 0.05$) reduction in initial juiciness, sustained juiciness, myofibrillar tenderness, and overall tenderness. The parameters for connective tissue amount, pork-flavor intensity, and off-flavor intensity were not affected by inclusion of hybrid rye (Table 3.1).

Bacon Trained Sensory Evaluation

As hybrid rye increased in the diet from 0 to 100% during the growing-finishing period, there was no impact on texture, saltiness, smoke intensity, bacon flavor, or off-flavor intensity (Table 3.1).

Warner-Bratzler Shear Force

Increasing the replacement rate of corn for hybrid rye during the growing-finishing period resulted in a linear ($P < 0.05$) increase in WBSF (Table 3.1).

Chop Bloom Color Analysis

Increasing the inclusion level of hybrid rye during the growing-finishing stage resulted in a tendency toward a linear ($P < 0.10$) and a quadratic increase ($P < 0.05$) in a*. There was a linear ($P < 0.01$) and quadratic increase ($P < 0.05$) in b* as the inclusion of hybrid rye increased to 75% replacing corn in the diet. There was no effect on L* recorded in any loin chop sample (Table 3.2).

3.5 Discussion

The consumer's decision to purchase pork is commonly associated with the product's presentation in the meat case (i.e., color, fat content, water holding capacity) (Choe et al., 2016). The ingredients included in the diet during the growing-finishing phase of pigs can play a major role on these characteristics (Baltić et al., 2011). It's important to understand how alternative ingredients used affect the eating experience of pork products because of the influence it has on promoting product distribution , environmental, and economic sustainability for the swine industry.

In this effort, we hypothesized that increasing replacement of corn (0-100%) with hybrid rye during the growing-finishing stage would reduce pork quality attributes for product sensory evaluation, WBSF, and chop bloom color. The results of this study support our hypothesis were replacing corn with hybrid rye negatively impacted pork quality of loin parameters (i.e., reduced juiciness and tenderness of loins based on panelist assessment and increased WBSF); although, there was no effect on bacon sensory analysis.

To verify the optimal inclusion rate of hybrid rye in small grain-based (wheat-barley) diets, Lisiak et al. (2023) determined that including 60% (replaced 30% wheat; 30% barley) hybrid rye during the growing-finishing period had no impact on loin sensory parameters (i.e., smell, flavor, juiciness, or tenderness) or WBSF scores. The linear decrease in WBSF noted in this work may be related to the sources replaced (corn; wheat-barley) or the greater inclusion level of hybrid rye (77.22%; 60%) in comparison to that of Lisiak et al. (2023).

In previous literature, McGhee et al. (2021) addressed hybrid rye in corn-based diets and reported that increased the replacing rate of corn (0-100%) with hybrid rye had no impact on loin WBSF, bloom color or panelist scores for tenderness and juiciness; however, a linear reduction in loin flavor was reported. The lack of consistency between the results of McGhee et al. (2021) and the current study on trained, panelist scores and WBSF may reflect the variation in procedures to record loin parameters. McGhee et al. (2021) assessed WBSF with an average of four cores with a crosshead speed of 198 mm/minute, compared to the current study that used six cores with a blade speed of 250 mm/minute. In preparation for the trained, sensory panel of McGhee et al. (2021), loin chops were cooked to an internal temperature of 63°C, compared to current data that cooked chops to reach an internal temperature of 71°C. The difference in samples size, crosshead speed, and cooking methods may be related to why there was a notable increase in WBSF and decrease in panelist scores for tenderness and juiciness in this trial.

Differences in sensory analysis between McGhee et al. (2021) and the current study may also be related to the differences in pig feed intake. The rate of consumption during the growing-finishing period can impact pork quality (i.e., WBSF, tenderness, juiciness) (Ellis et al., 1996; Blanchard et al., 1999; Cameron et al., 1999; Apple, 2010). Reduced WBSF and greater panelist scores for tenderness and juiciness has been reported in pigs that achieved ad libitum intake compared to pigs that consumed 75-80% of the diet (Ellis et al., 1996; Blanchard et al., 1999; Cameron et al., 1999; Apple, 2010). McGhee et al. (2021) recorded a linear reduction in ADFI only during the growing phase (d1-35) and a tendency to reduce in the late-finisher phase (d 70-97); while there was a decrease in ADFI during the entire growing-finishing period (d 1-89) in the current study (Chapter 2, Section 2.4). It is important to note that, even though differences were recorded in the current study with increasing (0-100%) the replacement rate of corn with hybrid rye, the variation in quality measures are within the standard range of responses from "typical" consumers (AMSA, 2015). Thus, it is unlikely that these differences in product quality attributes are detectable by humans.

Along with pork palatability, product color is also a major factor for purchasing decisions (Apple, 2010). Pork color or "bloom" is related to the rate in which oxygenation occurs withing the muscle tissue (Brewer et al., 2001). The typical period to assess meat color is 24 hours after fabrication (Brewer et al., 2001; Lindahl et al., 2006; Limsupavanich et al., 2017). When bloom color was assessed 48 hours after evisceration, Lisiak et al. (2023) investigated the impact of including hybrid rye (0-60%) in barley-wheat control treatments and recorded only a negative impact on a* (redness), when rye inclusion reached 20%, with no impact on L* (lightness) or b* (yellowness). Even though the results for L* of the current study mirror that of Lisiak et al. (2023), the values recorded for a* and b* are conflicting, as hybrid rye inclusion at 70% caused a linear and quadratic increase.

In this work, color was assessed after samples were vacuum-sealed and frozen for 50 days (-20°C). The results of the current study, compared to that of Lisiak et al. (2023) could be attributed to the timing of the analysis or sample preparation used before color assessment occurred. Rosenvold and Andersen (2003) recorded that vacuum-sealed pork stored up to 8 days increased lightness, redness, and yellowness. This may support current results on pork bloom, as loins were chilled for 5 days (0-4°C) before fabrication, packaging, and freezing.

To address the effects of freezing on pork bloom, Zhu et al. (2004) evaluated meat color using unfrozen (control) and various freezing methods (i.e., air blast (-20°C), liquid immersion (-20°C), pressure shift (100 MPa, -11 to -8.7°C; 150 MPa, -16.5 to -14.4°C; 200 MPa, -21.5 to -20.7°C). It was determined that L* and a* only increased when high pressure shift (150 MPa; 200 MPa) freezing was used. Zhu et al. (2004) also reported higher b* values in products that had been frozen, compared to the unfrozen control. This data could reflect why there was a linear and quadratic increase in a* and b* of the current study. While the color score analysis in this work may have limited application to fresh pork, it relevant to distribution of frozen products in international markets (Brewer et al., 2001).

Even though there was a reduction in IV, the lack of effect of increasing hybrid rye on belly sensory analysis was somewhat expected. One of the primary variables influencing bacon quality is the fatty acid profile of feed ingredients used in growing-finishing diets (Apple, 2010). As it has been reported that reducing the concentration of saturated fatty acids (i.e., steric acid) in pork products may reduce the risk of cardiovascular disease in humans, it is supported to include ingredients (i.e., high-oil corn, soybean oil) that are higher in poly-unsaturated fatty acids (i.e., linoleic acid). The conundrum is that if these ingredients are fed continuously (i.e., growing-finishing period) the inclusion rate should not exceed recommendations (≤ 10%) to prohibit any impact on belly firmness or fabrication efficiency (i.e. ,slicing ability) (St. John et al., 1987; Shackelford et al., 1990; Rentfrow et al., 2003; Lammers et al., 2007).

Generally, it is standard practice to avoid nutritional techniques during the growing-finishing period that create pork products containing higher levels of poly-unsaturated fatty acids (i.e., < 14% linoleic acid) and short chain fatty acids (i.e., < 15% steric acid) to prevent bellies from having softer fat (NPPC, 2000; Rentfrow et al., 2003). Rentfrow et al. (2003) determined that feeding conventional, corn-based (86.25%) diets with a proportion of steric (12.63%) and linoleic acid (9.05%) had no impact on belly firmness. When comparing the fatty acid profile of hybrid rye-based diets (67.45%), McGhee et al. (2021) reported a lower proportion of steric acid (4.01% ± -0.40) and higher amount of linoleic acid (45.13% ± -3.14) in the small grain than corn.

Because the current study reported no effect on belly quality with increasing the replacement rate of corn for hybrid rye, it is suggested that even though the unsaturated fat content (i.e., linoleic acid) is higher in hybrid rye than corn, the total percentage of ether extract is substantially lower in rye (Bono) (1.24%) than corn (3.61%) (McGhee, 2019). The overall fat content in hybrid rye, compared to corn could reflect why there was no impact on belly quality.

Even though this study only considered the effects of hybrid rye on bellies using a trained, sensory panel and not instrumental methods (i.e., color scale, fatty acid profile), it is concluded that increasing the replacement rate of corn for hybrid rye (0-100%) in commercial swine diets does not impact consumer preference on bacon texture, flavor, smoke intensity, or smokiness.

Conclusion

In conclusion, this study revealed that increasing the replacement rate of corn (0-100%) with hybrid rye during the growing-finishing period negatively impacted loin chop sensory attributes and WBSF. It is important to note that even with the negative impact on panelist preference for loin texture and flavor when rye exceeded 40% in the diet, the positive influence on redness (a*) and yellowness (b*) when the percentage of hybrid rye increased to 70% may benefit exported pork products. Because of the lack of effect on belly parameters, it is concluded that increasing the inclusion of hybrid rye does not impact bacon quality and subsequently, the value of the primal cut.

Table 3.1 Effect of increasing hybrid in growing-finishing diets on loin and bacon quality[1]

	Hybrid Rye Replacing Corn[2], %					*P*-values	
Items	0	40	70	100	SEM	Linear	Quadratic
Loin Parameters							
Initial Juiciness[3]	54.5	53.9	51.0	51.4	1.19	0.027	0.861
Sustained Juiciness[3]	48.1	48.3	45.0	45.2	1.28	0.035	0.787
Myofibrillar Tenderness[3]	61.8	61.8	57.4	59.1	1.35	0.013	0.682
Connective Tissue Amount	1.66	0.76	1.84	1.69	0.20	0.775	0.481
Overall Tenderness[3]	60.8	60.4	56.5	57.7	1.35	0.012	0.744
Pork-Flavor Intensity	28.6	29.1	28.5	28.6	0.66	0.756	0.685
Off-Flavor Intensity	0.00	0.08	0.00	0.00	0.04	0.771	0.238
WBSF[4], kg	2.39	2.46	2.78	2.64	0.10	0.005	0.291
Belly Parameters							
Texture	54.3	52.0	54.2	57.1	2.23	0.339	0.199
Saltiness	53.0	54.6	52.5	54.2	0.78	0.560	0.938
Smoke Intensity	56.3	57.7	58.0	57.1	1.27	0.416	0.166
Bacon Flavor	64.2	64.4	64.0	64.1	0.97	0.822	0.846
Off-Flavor Intensity	0.03	0.10	0.07	0.02	0.05	0.816	0.158

[1]A total of 88 pigs were collected during the second marketing event (d 76) to provide 22 replicates per treatment.
[2]Hybrid rye replaced corn at a rate of 0, 40, 70, and 100%.
[3]Peak temperature used as covariate in statistical analysis.
[4]WBSF = Warner Bratzler shear force.

Table 3.2 Effects of increasing hybrid rye in growing-finishing diets on chop bloom color[1]

	Hybrid Rye Replacing Corn[2], %					*P*-values	
Item[3]	0	40	70	100	SEM	Linear	Quadratic
L*	58.3	58.7	56.4	59.0	0.57	0.922	0.106
a*	16.9	17.5	18.8	17.4	0.37	0.058	0.017
b*	14.5	15.7	17.2	16.1	0.41	0.001	0.016

[1]A total of 88 pigs were collected during the second marketing event (d 76) to provide 22 replicates per treatment.
[2]Hybrid rye replaced corn at a rate of 0, 40, 70, and 100%.
[3]All loin chop samples were frozen for 50 days prior to data collection.

4.0 FINAL DISCUSSION

As swine producers are urged to quantify their acts of sustainability by using alternative techniques established by the We Care Act, the question remains what factors affect their ability to achieve "sustainable agriculture?" Even though corn and soybeans are traditionally used in swine diets in the U.S. Corn Belt, the environmental demands to propagate these ingredients significantly impairs (50-60%) the total environmental footprint of swine production. To help alleviate this detriment on land resources, producers are tasked to utilize small grains in diet formulation because of the inverted effect these cereals have on field conservation (i.e., reducing field fallow, improving soil health) and the agronomic supply chain. It's important that swine producers and crop growers evolve their techniques used to complement both commodity groups because of the total impact they both have on sustainable agriculture.

Thus, the objective of this thesis was to focus on alternative ingredient utilization in U.S. swine diets, specifically hybrid rye, and how this small grain may influence agronomic sustainability as a cover crop, growing-finishing pig performance, carcass characteristics, and product quality when replacing corn in a commercial setting. While this research does consider hybrid rye as an alternative grain in commercial swine diets, the sustainability metrics (i.e., agronomic throughput, milling efficiency) associated with incorporating this small cereal in crop production in the U.S. Corn Belt still needs to be determined.

To address the effects of hybrid rye on growth performance, it was recorded that, as the replacement rate of corn for hybrid rye increased (0-100%) during the growing-finishing stage, there was a negative impact on BW, ADG, and ADFI. It is assumed that because intake and gain decreased overall, it reflects why there was no effect on G:F. It is also suggested that if diets had been formulated to be isocaloric or isonitrogenous, the impact on pig performance would have been less detrimental. Due to the physiochemical properties (i.e., non-starch polysaccharides, resistant starch, oligosaccharides) of hybrid rye, it is assumed that the complexity of fiber constituents (15.16%) in this small grain prolonged satiation in pigs fed higher levels of hybrid rye (40-100%), compared to the pigs fed the corn-based diet (Li et al., 2021).

As research continues to investigate the effects of feeding hybrid rye to pigs, some work has looked at non-nutritional feed additives to promote nutrient utilization. For example, including a multi-carbohydrase enzyme (e.g., 1400 units/g β- glucanase and 4500 units/g xylanase) improved G:F in pigs fed diets that replaced wheat with hybrid rye (Smit et al., 2019). There is also data that verified that rye-based diets being supplemented with microbial phytase (1,000 units/g) improved available phosphorus by 13.2% and reduced phosphorus excretion by 0.28% (McGhee and Stein, 2019). To apply this information to the current study, it is suggested that including exogenous enzymes in diet formulation could promote the feeding value of hybrid rye in commercial diets and relay an improvement in sustainable swine production. This becomes controversial though, because of the added expense of including feed additives in commercial swine diets.

Due to the reduction in pig performance during the growing-finishing stage, it reflects why there was a relaying reduction on carcass characteristics for HCW, BF, % yield, and IV. Even with the detrimental effects on carcass parameters, we can conclude that the pigs fed rye-based diets may contain products that are of higher value to international markets because of the consumer's preference for pork to exhibit harder, white fat, which is the result of a lower IV.

Because consumer acceptability relates to, not only the fat composition of the product, but also traits for texture, flavor, and pigmentation, the results from this study conclude that increasing the inclusion of hybrid rye had a negative impact on loin WBSF, panelist scores for on initial juiciness, sustained juiciness, myofibrillar tenderness, and overall tenderness. There was a positive influence on a* and b* when loins were frozen for 50 days before analyzing bloom color. Although this data assumes a detriment on consumer acceptability for fresh pork, it may aid in marketing frozen products and promote distribution internationally. The lack of effect on belly sensory can also be assumed as a benefit for the swine industry because of the immense consumption of bacon products in the U.S.

While this thesis only focused on alternative practices in pig farming regarding small grain utilization, there is still a substantial amount of research that needs to be conducted to improve the total impact of U.S. swine production on sustainability metrics.

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