The effects of alternative feeding strategies without zinc oxide in nursery swine diets and high phytase supplementation on sow and litter performance

by

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Abstract

Two experiments were conducted to determine the effect of crude protein level in diets containing coarse wheat bran with or without pharmacological levels of Zn (provided by zinc oxide: ZnO) on growth performance and fecal dry matter of swine (n = 360 or n = 650 pigs for experiment 1 and 2, respectively). A third experiment used 360 nursery pigs to evaluate the effects of insoluble fiber source and crude protein level on growth performance and fecal dry matter. Experiment 4 used 109 sows to evaluate the effect of increasing units of Ronozyme HiPhos phytase in lactation diets on sow and litter performance. In Exp. 1, pigs fed pharmacological levels of Zn had improved growth performance. However, increased performance was not observed for pigs fed high levels of Zn in Exp. 2. Reducing crude protein and subsequently SID Lys in diets with coarse wheat bran in an attempt to reduce the occurrence of post-weaning diarrhea did improve fecal dry matter but did not maintain or improve growth performance. Pigs fed diets supplemented with high levels of feed grade essential amino acids did not have improved growth. Improvements in feed efficiency were observed for pigs with the addition of non-essential amino acids to diets containing coarse wheat bran. In Exp. 3, reducing crude protein level resulted in decreased growth performance while fecal dry matter was increased on day 17. The source or inclusion of dietary insoluble fiber had no effect on growth performance, while the inclusion of cellulose as a fiber source improved fecal dry matter. For Exp. 4, increasing phytase from 0 to 3,000 FYT/kg increased feed intake in late lactation and overall intake tended to increase. Linear improvements in pig survivability were observed with increasing phytase. Overall litter gain and weaning weight was maximized for sows fed 1,000 FYT/kg.

Table of Contents

List of Tables

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Chapter 1 - Effects of low dietary crude protein and coarse wheat bran as an alternative to zinc oxide in nursery pig diets

Abstract

Two experiments were conducted to determine the effects of crude protein level in diets containing coarse wheat bran (CWB) with or without pharmacological levels of Zn (provided by zinc oxide: ZnO) on growth performance and fecal dry matter of nursery pigs. In Exp. 1, 360 weanling barrows (Line 200 × 400, DNA, Columbus, NE, initially 5.6 kg) were allotted to 1 of 6 dietary treatments from d 0 to 21 after weaning with 5 pigs per pen and 12 pens per treatment. Treatments included a positive control diet (21% crude protein, CP) with 3,000 mg/kg Zn in phase 1 and 2,000 mg/kg in phase 2, negative control (21% CP) with 110 mg/kg added Zn, and four treatments containing 4% CWB and 110 mg/kg added Zn and formulated to contain 21, 19.5, 18, or 16.5% CP. The two control diets and 21% CP CWB diet contained 1.40% standardized ileal digestible (SID) Lys in phase 1 and 1.35% SID Lys in phase 2, while the 19.5, 18, and 16.5% CP diets contained 1.33, 1.25 and 1.20% Lys, respectively in both phases. Pigs fed the positive control diet containing pharmacological ZnO had increased ($P < 0.05$) ADG, ADFI, and G:F compared to the negative control and the 21% CP CWB diet. Reducing CP (concurrently with SID Lys) in diets containing CWB decreased ADG and G:F (linear, $P = 0.002$); however, fecal dry matter percentage increased (linear, $P = 0.005$). In Exp. 2, two groups of 300 and 350 pigs, initially 7.0 and 6.2 kg, respectively, were used with 5 pigs per pen and 26 replicates per treatment. All dietary treatments were fed for a 13-day period, contained 4% CWB, and consisted of: 1) positive control with ZnO providing 2,000 mg/kg of Zn and 21% CP (1.35% SID Lys); 2) diet with no ZnO and 21% CP; and 3 treatments with no ZnO formulated to 18% CP and 3) 1.2% SID Lys; 4) 1.35% SID Lys by the addition of feed grade amino acids, and

5) treatment 4 with the addition of non-essential amino acids (NEAA; Gly and Glu). Pigs fed 21% CP with ZnO had increased ($P = 0.001$) ADG compared to those fed 18% CP (1.35% SID Lys) with high levels of feed grade amino acids or those fed the reduced SID Lys (1.2%) diet. Overall G:F was improved ($P < 0.001$) for pigs fed 21% CP diets and those fed the 18% CP diet with NEAA compared to pigs fed 1.2% SID Lys and pigs fed high levels of feed grade amino acids. Fecal dry matter was increased for pigs fed the reduced SID Lys diet. In conclusion, reducing crude protein (and subsequently SID Lys) decreased nursery pig growth performance and may affect fecal dry matter.

Key Words: crude protein, fecal dry matter, lysine, nursery pig, wheat bran, zinc oxide

Introduction

The weaning process is often described as the most stressful event of a pig's life due to abrupt dietary, physiological, social, and environmental changes (Pluske, 2016). Pigs frequently experience a period immediately after weaning termed the post-weaning growth lag, which results from low feed intake initiated by weaning stress and coupled with an immature digestive system. Reductions in feed intake can also be attributed to a dietary change from a highly digestible liquid diet from the sow to a solid, starch-based diet, leading to intestinal morphology implications such as intestinal villous atrophy and crypt hyperplasia (Heo et al., 2012). This results in reduced enzymatic and absorptive capacity ultimately impairing the digestion of nutrients (Spreeuwenberg et al., 2001). Newly weaned pigs also have increased susceptibility to gastrointestinal issues and enteric diseases such as post-weaning diarrhea (PWD), primarily occurring in the first 2 weeks after weaning associated with the proliferation of β-haemolytic *Escherichia coli (E. coli)* (Pluske et al., 1997).

Nursery swine diets often include pharmacological doses of Zn to mitigate PWD and to improve growth performance (Carlson et al., 1999). High dietary concentrations of Zn from ZnO (2,000 to 3,000 ppm) have been observed to possess antimicrobial effects while also decreasing intestinal mucosal inflammation (Ou et al., 2007). However, the inclusion of high Zn levels or antimicrobials in swine diets has been banned or restricted in some countries due to environmental concerns and the risk of antibiotic resistance (Heo et al., 2012). Due to concerns of similar regulations on pharmacological levels of Zn in the United States, an alternative nutritional strategy offering similar growth and physiological benefits to nursery pigs that improves the transition of weaning is desired for the swine industry.

Newly weaned pigs struggle to digest high protein diets due to underdeveloped proteolytic enzymes, therefore resulting in undigested protein entering the large intestine and serving as a substrate for bacterial fermentation and proliferation (Jeaurond et al., 2008). The fermentation of undigested protein by intestinal microbiota has been determined as a significant contributing factor to PWD (Pluske et al., 2002). As protein fermentation occurs, by-product concentrations of polyamines, ammonia, indole, and phenol products are increased and can be potentially toxic to the pig (Halas et al., 2007). Consequently, colonic pH is increased with a high protein diet, creating a neutral environment which provides favorable conditions for enterotoxigenic species such as *Bacteroides* and *Clostridium* (Jensen, 2001).

To promote fecal consistency and intestinal health, feeding a low protein diet supplemented by crystalline amino acids in the post-weaning period reduces protein fermentation in the gastrointestinal tract (GIT) and lowers the incidence of PWD (Wang et al., 2018; Yue and Qiao, 2008). However, negative implications on growth performance have been observed when dietary crude protein is reduced more than 4 percentage points, thought to result from

deficiencies in amino acids, either essential or non-essential to the pig (Gloaguen et al., 2014; Nyachoti et al., 2006) or from excessive amino acid catabolism occurring in the liver (Sun et al., 2020). Another method to improve post-weaning performance is by promoting the proliferation of commensal microbiota with the inclusion of fibrous ingredients that block the attachment of bacteria to the intestine (Becker et al., 2009). As fiber increases in the diet, beneficial microbial populations proliferate and produce volatile fatty acids such as butyrate, the primary oxidative fuel source of intestinal enterocytes (Kim et al., 2012). Molist et al. (2010) presented that 4% coarse wheat bran decreased the ability of *E. coli* to attach to the intestinal mucosa of *E. coli* challenged pigs, while Molist et al. (2011) modified the pig's microbiota to proliferate increased counts of fiber degrading species with the inclusion of 4% coarse wheat bran. The insoluble fiber portion of coarse wheat bran perhaps offers similar antimicrobial properties to ZnO (Molist et al., 2011) as insoluble fiber increases digesta passage rate, therefore limiting colonization of enterotoxigenic bacteria in the hindgut (McDonald et al., 2001). Data is lacking that shows the effects of combining different ZnO-replacement strategies on pig performance and fecal dry matter. Therefore, the objective of these experiments was to determine the effect of adding coarse wheat bran with reduced crude protein level on the growth performance and fecal dry matter of nursery pigs in diets without pharmacological levels of zinc oxide.

Materials and Methods

The Kansas State University Institutional Animal Care and Use Committee approved the protocols used in these experiments. The studies were conducted at the Kansas State University Segregated Early Weaning Facility and the Kansas State University Swine Teaching and Research Center in Manhattan, KS. Each pen contained a 4-hole, dry self-feeder and cup waterer for ad libitum access to feed and water.

Experiment 1: Crude protein level and coarse wheat bran

In Exp. 1, a total of 360 barrows (Line 200 × 400, DNA, Columbus, NE, initially 5.6 kg) were used in a 45-d growth trial. Pigs were weaned at approximately 21 d of age and following arrival to the research facility, were randomized to pens and then allotted to 1 of 6 dietary treatments with 5 pigs per pen and 12 pens per treatment. Treatment diets were offered in two dietary phases (phase 1 fed from d 0 to 7 and phase 2 from d 7 to 21 post-weaning; Tables 1-1 and 1-2). A post-treatment period with a common diet was fed from d 21 to 45 (Table 1-3). Dietary treatments included a positive control diet (21% CP) with 3,000 mg/kg Zn from ZnO in phase 1 and 2,000 mg/kg in phase 2, a negative control diet (21% CP) with 110 mg/kg added Zn, and four treatment diets that contained 110 mg/kg added Zn and 4% coarse wheat bran and were formulated to contain either 21, 19.5, 18, or 16.5% (CP). Diets were formulated to a maximum SID Lys: digestible CP level of 6.35% based on Millet et al. (2018). Therefore, standardized ileal digestible Lys was lowered in order to reduce crude protein level for the low CP diets with wheat bran to limit amino acid deficiencies relative to Lys and to maintain the ratio. The two control diets and the 21% CP wheat bran diet contained 1.40% standardized ileal digestible (SID) Lys in phase 1 and 1.35% SID Lys in phase 2, while the 19.5, 18, and 16.5% CP diets contained 1.33, 1.25 and 1.20% SID Lys, respectively in both phases. All diets were formulated to obtain a similar ratio of essential SID amino acids to SID Lys with feed grade amino acids. Ingredient nutrient values as well as their SID coefficients used in diet formulation were derived from NRC (2012). The first phase was fed in pellet form and the following phases were fed as meal.

All dietary treatments were manufactured at the Kansas State University O. H. Kruse Feed Technology Innovation Center in Manhattan, KS and were corn-soybean meal-based. The average particle size of the coarse wheat bran included in the experimental diets was 1,061

microns. Particle size analysis was done using the ANSI/ASAE S319.2 method with a Ro-tap 13-sieve Shaker using flow agent and sieve agitators as recommended by Kalivoda et al. (2017). Samples of complete diets were collected during bagging with a sample collected from every third bag and pooled into one homogenized sample per dietary treatment. Samples were stored at -20°C until they were subsampled and submitted for analysis (Ward Laboratories, Kearney, NE) for dry matter (method 935.29; AOAC International 2019), CP (method 990.03; AOAC International, 2019), crude fiber (ANKOM Technology, 2005), ADF (ANKOM Technology, 1998), NDF (ANKOM Technology, 2017), Ca (method 6.3; Kovar, 2003), P (method 6.3; Kovar, 2003), and Zn (Campbell and Plank, 1991).

Pigs and feeders were weighed every 7 d to determine ADG, ADFI, and G:F. Fecal samples were collected from the same three pigs per pen on d 7, 14, 21, and 45 of the study. Fecal samples were collected into clean, single use zipper storage bags and were then stored at -20°C until fecal dry matter analysis. Equal fecal samples from each pig were pooled by pen respective of day of collection and dried at 55°C in a forced air oven for 48 h. Fecal dry matter was determined as follows: (dried sample weight at 48 h – pan weight) / (initial wet sample weight – pan weight) × 100.

Experiment 2: Dietary low crude protein strategies with coarse wheat bran

In Exp. 2, two groups of 300 pigs (Line 241 × 600, DNA, Columbus, NE, initially 7.0 kg) and 350 pigs (initially 6.2 kg) were used in a 13-d growth trial. Pigs were weaned at approximately 21 d of age and placed in pens of 5 pigs each based on initial BW and gender. The first group within Exp. 2 were fed a common pelleted diet with pharmacological levels (3,000 mg/kg Zn from ZnO) for 10 d after weaning, and the second group was fed diets without pharmacological levels of ZnO for 14 d after weaning and prior to the start of the experiment. At

10 or 14 d after weaning, which was considered d 0 of the trial, pens of pigs were randomly allotted to 1 of 5 dietary treatments in a randomized complete block design with BW as the blocking factor. In total, there were 5 pigs per pen and 26 pens per treatment with 12 replicates per treatment in the first group and 14 replicates per treatment in the second group of pigs.

Treatment diets were offered in mash form and in one dietary phase (Table 1-4). All dietary treatments contained 4% coarse wheat bran and consisted of: 1) positive control with ZnO providing 2,000 mg/kg of Zn and 21% CP (1.35% SID Lys); 2) a diet with 110 mg/kg added Zn and 21% CP (1.35% SID Lys); 3) a diet with 110 mg/kg added Zn formulated to 18% CP (1.2% SID Lys); 4) an 18% CP diet with 110 mg/kg added Zn formulated to 1.35% SID Lys by the addition of feed grade amino acids, and 5) treatment 4 with the addition of non-essential amino acids (Gly and Glu). Diet 3 was formulated to 18% CP while adding feed grade amino acids until the minimum Ile:Lys requirement of 52% was met. L-Ile and L-His were added along with other feed grade amino acids to formulate diet 4 to 1.35% SID Lys. The non-essential AA Glu and Gly were added to diet 5 as the combination of Gly and nitrogen from an additional AA has been determined to be required in low CP diets (Powell et al., 2011). A common post-treatment diet was fed from d 13 to 27 to the second group of pigs in Exp. 2 (Table 1-5).

Fecal samples were collected from the same three pigs on d 0, 7, and 13 for group 1, and on d 0, 6, 13, 20, and 27 for the second group of pigs. Feed manufacturing and diet and fecal sample collection and analysis were identical to procedures used in Exp. 1.

Statistical Analysis

In Exp. 1, data were analyzed as a completely randomized design using the lmer function from the lme4 package in R (version 3.6.1 (2019-07-05), R Foundation for Statistical Computing, Vienna, Austria), with pen as the experimental unit and barn as a random effect. Pre-

planned linear and quadratic contrast statements were used to evaluate decreasing crude protein level. Contrast statements were used to evaluate the positive and negative control diets, the positive control vs. the 21% CP with coarse wheat bran diet, and the negative control vs. the 21% CP with coarse wheat bran diet. A repeated measures statement, with the random effect of barn, was used to analyze fecal dry matter percentages over time. Differences between treatments were considered significant at $P \leq 0.05$ and marginally significant at $0.05 < P \leq 0.10$.

Statistical analysis for Exp. 2 was performed using the lmer function from the lme4 package in R (version 3.6.1 (2019-07-05), R Foundation for Statistical Computing, Vienna, Austria). Growth performance data were analyzed as a completely randomized block design using pen as the experimental unit and treatment as a fixed effect. Weight block was included in the model as a random effect. A repeated measures statement with a random effect of block, was used for analyzing fecal dry matter percentages over time. There were no significant treatment × group interactions, thus data from groups 1 and 2 were combined to evaluate growth performance during the experimental period (d 0 to 13). Differences between treatments were considered significant at $P \leq 0.05$ and marginally significant at $0.05 < P \leq 0.10$.

Results

Experiment 1

Results of chemical analysis of diets in Exp. 1 were consistent with formulation (Table 1-6).

In phase 1 (d 0 to 7), no evidence for differences were observed for pigs fed the positive control compared to the negative control or compared to pigs fed the 21% CP wheat bran diet (Table 1-7). For pigs fed diets with decreasing CP, ADG and G:F decreased (linear, $P < 0.001$). Pigs fed diets with 21% CP and coarse wheat bran had increased (linear, $P = 0.001$) BW on d 7

compared to pigs fed lower CP diets. On d 7, there was marginal evidence for differences for pigs fed the positive control to have (Table 1-8) increased fecal dry matter compared to pigs fed the 21% CP coarse wheat bran diet ($P = 0.059$) without pharmacological levels of ZnO. Fecal dry matter percentage increased on d 7 (linear, $P = 0.029$) for pigs fed diets with decreasing CP level.

From d 7 to 21, which corresponds to phase 2, decreasing dietary CP resulted in decreased (linear, $P = 0.05$) ADG, G:F, and BW on d 21. Pigs fed the positive control diet containing pharmacological levels of Zn had increased ($P < 0.05$) ADG, ADFI, G:F, and BW on d 21 compared to the negative control diet without added ZnO and compared to the 21% CP wheat bran diet.

During the experimental diet phase (d 0 to 21), pigs fed the positive control diet containing ZnO had improved ($P < 0.05$) performance across all growth response criteria measured compared to the negative control and the coarse wheat bran diet with 21% CP. Decreasing crude protein in diets containing coarse wheat bran resulted in decreased (linear, $P = 0.002$) ADG and G:F, and a marginally significant decrease (linear, $P = 0.065$) in ADFI. Pigs fed wheat bran diets with lower CP had increased (linear, $P = 0.006$) fecal dry matter, suggesting more solid feces and lower instances of loose stool.

A post-treatment diet was fed from d 21 to 45. Pigs previously fed the wheat bran diet with 21% CP had an increase ($P = 0.033$) in ADG compared to pigs fed the positive control diet. Feed efficiency improved for pigs fed the wheat bran diet with high CP ($P = 0.007$) and for the pigs previously fed the negative control diet ($P < 0.001$) compared to the positive control diet with pharmacological levels of Zn. A marginal decrease (linear, $P = 0.058$) in ADFI was observed as crude protein fed in the previous period decreased; however, a marginal

improvement (linear, $P = 0.078$) in G:F was observed for the pigs previously fed decreasing crude protein levels. Fecal dry matter percentage (Table 1-8) on d 45 decreased (linear, $P = 0.002$) for pigs previously fed diets with decreasing CP, while dry matter was increased for pigs previously fed the negative control compared to the positive control ($P = 0.004$) and increased for those previously fed the 21% CP wheat bran diet vs. the positive control ($P = 0.016$).

Overall from d 0 to 45, decreasing CP resulted in decreased (linear, $P < 0.050$) ADG, ADFI, and BW on d 45. Pigs fed the positive control diet had increased ($P < 0.050$) ADG, ADFI, and greater ($P = 0.056$) BW on d 45 compared to those fed the negative control. Overall, no evidence for differences in any growth criteria measured was observed for pigs fed the positive control vs. pigs fed the 21% CP diet with coarse wheat bran.

Experiment 2

For Exp. 2, chemical analysis of diets (Table 1-9) resulted in values consistent with diet formulation with analyzed Zn slightly lower than formulated. Analyzed CP was consistent with formulated values; however, for the diet with added non-essential feed grade amino acids, CP analyzed at greater than 18% CP due to the nitrogen from the nonessential amino acids added to the diet. Analysis of crude fiber and NDF resulted in higher values for group 2 than group 1; however, diet formulations and coarse wheat bran ingredient sources were the same for both groups.

Pigs in group 1 were fed a common diet which contained pharmacological levels of Zn for 10 d before experimental diets were fed. For group 2, pigs were fed a diet for 14 d containing no pharmacological Zn prior to the start of the trial. During data analysis, no group by treatment interactions were observed, therefore data was combined for both groups.

Pigs fed 21% CP with ZnO had increased ($P < 0.05$) ADG compared to pigs fed 18% CP with 1.2% Lys and 18% CP with high levels of feed grade amino acids (Table 1-10). Additionally, pigs fed the 18% CP diet supplemented with high levels of amino acids had decreased ($P < 0.05$) ADG compared to pigs fed the 21% CP diet with no ZnO. Overall G:F was increased ($P < 0.05$) for pigs fed 21% CP diets regardless of ZnO inclusion and for pigs fed the 18% CP diet with added non-essential amino acids compared to the other treatments. Final BW on d 13 was heaviest ($P < 0.05$) for pigs fed 21% CP diets with ZnO compared to pigs fed 18% CP diets. Pigs fed 21% CP without ZnO also had increased ($P < 0.05$) final BW compared to pigs fed 18% CP with high levels of feed grade amino acids. Fecal dry matter percentage (Table 1-11) on d 6 was increased ($P < 0.05$) for pigs fed the 1.2% SID Lys diet compared to pigs fed 21% CP diets with other dietary treatments intermediate. Marginal evidence for treatment differences was observed ($P = 0.084$); however increased ($P < 0.05$) fecal dry matter on d 13 was observed for pigs fed the reduced Lys diet (1.2% SID Lys) compared to the pigs fed 21% CP diet without ZnO. From d 13 to 27, group 2 was fed a common post-treatment diet. No evidence for differences in any growth response criteria measured was observed across dietary treatments.

Discussion

Post-weaning diarrhea is a common condition in pigs classified by consistent discharge of loose, watery feces during the first 2 weeks after weaning (Rhouma et al., 2017). This condition represents a major economic issue for the swine industry and can result in dehydration, reduced feed intake, nutrient digestibility, growth, and, in severe cases, even death (Heo et al., 2012). However, feeding pharmacological levels of Zn (usually around 2,000 – 3,000 mg/kg of Zn) to diminish PWD (Katouli et al., 1999; Højberg et al., 2005) and to promote growth after weaning has been a widely accepted dietary tool (Case and Carlson, 2002, Hill et al., 2000). Zinc is an

essential trace mineral with the NRC (2012) recommended level for 5 to 11 kg pigs being 100 mg/kg of Zn. As regulatory restrictions on the use of pharmacological levels of Zn increase, an alternative dietary strategy to minimize PWD while promoting nursery pig growth is needed.

Pigs fed diets supplemented with pharmacological levels of ZnO in Exp. 1 had improved performance for all growth response criteria measured during the experimental period compared to pigs fed the negative control with no added ZnO or the high CP diet with coarse wheat bran. Overall, pigs previously fed diets containing pharmacological levels of ZnO had increased ADG, ADFI, and heavier BW on d 45 compared to pigs fed the negative control. Improvements in performance for pigs fed diets with ZnO in the present research are consistent to results observed in other studies feeding pharmacological levels of ZnO (Smith et al., 1997; Carlson et al., 1999; Case and Carlson, 2002; Molist et al., 2011). High doses of Zn have been proposed to increase feed intake, as Yin et al. (2009) observed increased ghrelin levels, a hormone which stimulates feed intake and muscle growth in early-weaned pigs with ZnO supplementation. Evidence also exists that pharmacological Zn reduces intestinal mucosal inflammation, promoting increased nutrient digestibility and improved growth performance (Ou et al., 2007). In Exp. 2, the pigs in group 1 received a common starter diet prior to the start of the study that contained pharmacological levels of ZnO; however, performance during the experimental period was similar between pigs fed the 21% CP diet with ZnO or without ZnO. Therefore, pigs in the second group of Exp. 2 were fed a common diet with no pharmacological levels of Zn for 14 d prior to the start of the trial to determine if high Zn fed in a starter diet immediately post-weaning weakened the response to pharmacological levels of ZnO in the next feeding phase. However, as found in group 1, no response to pharmacological levels of Zn were observed, therefore the individual groups were combined. Growth responses to high levels of Zn are not always

observed (Schell and Kornegay, 1996; Martínez et al., 2005; Wilt and Carlson, 2009). These authors proposed that the lack of response could be due to low cases of scouring and high initial health status. Burrough et al. (2019) concluded that differences in trial designs, genetics, intestinal microbial populations, as well as environmental factors may attribute to the variable growth response in weaned piglets to pharmacological levels of Zn. No comparisons among pigs fed pharmacological levels of ZnO in Exp. 1 and Exp. 2 can be made due to different lengths of feeding ZnO, differing amounts of ZnO fed, and if Phase 1 diets contained ZnO or not.

Newly weaned pigs are commonly offered high protein (high amino acid concentration) diets due to a low feed intake capacity and a high potential for protein deposition (Gloaguen et al., 2014). Excessively high protein diets can initiate digestive issues for nursery pigs as undigested protein contributes to the proliferation of pathogenic bacteria in the gastrointestinal tract (Pluske et al., 2002; Wang et al., 2018). Excess amino acids are deaminated and urea is excreted through urine (van Milgen and Dourmad, 2015). Low crude protein diets have been shown to reduce inflammatory responses and the proliferation of enterotoxigenic *E. coli* strains associated with PWD (Kim et al., 2011; Opapeju et al., 2009); however, reductions in dietary CP content by reducing diet amino acid concentrations can result in compromised growth performance. The increased availability of crystalline L-Lys, DL-Met, L-Thr, L-Trp, L-Val, and L-Ile has enabled CP to be practically reduced in swine diets while maintaining high amino acid concentrations. Further reductions in dietary CP may be limited by dietary His levels and other unknown requirements for the next-limiting amino acid.

Lewis (2001) noted that reducing CP content by 2 percentage points allowed pig performance to be maintained, while further reductions in CP with crystalline amino acid supplementation have led to conflicting results. Several researchers have observed no reductions

in growth for pigs fed low CP diets supplemented with essential amino acids (Hansen et al., 1993; Jin et al., 1998; Le Bellego and Noblet, 2002). In Exp. 1, pigs fed diets with reduced crude protein and subsequently reduced SID Lys had decreased ADG, feed efficiency, and BW during the experimental period. Wellock et al. (2006) observed growth performance to be diminished when crude protein content was reduced from 23% to 13% CP and when SID Lys was not balanced. In support of the current findings, dietary CP could not be reduced below 16% CP before the performance of 8 to 25 kg pigs decreased when SID Lys was below the requirement for growth (Jansman et al., 2016). Diets in experiment 1 were formulated to a maximum SID Lys:digestible CP level of 6.35% as suggested by Millet et al. (2018) as the authors concluded a maximum Lys to digestible crude protein ratio of 6.35% is recommended to maintain an adequate amount of nitrogen to enable sufficient synthesis of non-essential amino acids. Thus, SID Lys decreased in the 19.5, 18, and 16.5% CP diets to maintain the Lys:digestible CP ratio in Exp. 1. The resulting deficiencies in SID Lys likely limited growth performance as dietary CP decreased.

Additionally, reduced growth performance was also observed in Exp. 2 for pigs fed decreasing CP regardless of whether the SID Lys levels were maintained at similar levels to the control diet or not. The results from the current studies agree to Nyachoti et al. (2006), who fed low CP diets (23 to 17% CP) balanced with essential amino acids and observed reduced final BW and overall ADG and ADFI by feeding diets containing less than 19% CP. Yue and Qiao (2008) also observed decreased overall performance and final BW for pigs fed diets with 17.2% CP compared to pigs fed 23.1% CP. Standardized ileal digestible Lys was balanced in these experiments, similar to Exp. 2, however performance was still reduced. Nyachoti et al. (2006) concluded that decreased performance in low CP diets could be due to other limiting amino

acids, as Yue and Qiao (2008) determined that deficiencies in non-essential amino acids such as glutamine (Gln), could be a driving factor in reduced performance. It has been suggested that minimal levels of amino acids classified as non-essential are also required by the pig (Wu, 2014).

Therefore, one of the objectives of Exp. 2 was to determine if growth performance could be maintained when feeding diets with similar SID Lys levels combined with the supplementation of either essential or non-essential amino acids. Growth was limited for pigs fed the 1.2% SID Lys diet compared to those fed diets with 1.35% which agreed with our hypothesis and the results of Exp. 1 where SID Lys was reduced. In Exp. 2, the addition of essential amino acids to achieve 1.35% SID Lys also did not improve growth performance. A study conducted by Opapeju et al. (2008) observed decreased growth in pigs fed low CP diets (17% CP) with balanced SID Lys supplemented with essential AA including Val and Ile. The authors claimed a shortage of indispensable AA in the low CP diet initiated poor performance. In the present study, the addition of non-essential amino acids Glycine (Gly) and Glutamic acid (Glu) was hypothesized to maintain growth or improve performance similar to pigs fed 21% CP diets. In Exp. 2, feed efficiency was improved for pigs fed 18% CP diets with the addition of non-essential amino acids. The results from Exp. 2 are similar to that of Gloaguen et al. (2014) in that feed efficiency was restored with the addition of L-Glu in a 14% CP diet. However, Silva et al. (2020) conducted a study comparing a control diet to a low CP diet with added Ser and Gly and a low CP diet with added Glu. The authors observed that ADG and final BW were reduced for pigs fed both low CP diets compared to pigs fed a 23.6% CP control diet. These findings are similar to Exp. 2 when Gly and Glu were supplemented to an 18% CP diet as final BW was reduced. A considerable issue with low CP diets is an insufficient supply of non-essential amino acids (Wu et al., 2018). Gloaguen et al. (2014) determined that amino acids that have been traditionally

determined to be non-essential may be limiting for growth in low CP diets**.** Wu (2014) suggests that dispensable AA, like Glu and Proline (Pro), regulate metabolic pathways and due to catabolism of non-essential AA in the small intestine of the pig, these dispensable AA should be included in diets to support the ideal protein requirement for optimal growth. Glycine has been identified as one of the first non-essential AA that may become limiting in a low CP diet, as Powell et al. (2011) demonstrated that performance was maintained with the supplementation of Gly and Arginine (Arg) or with Gly and Glu in 20- to 50-kg pigs, but not with the supplementation of Arg or Glu individually. Sun et al. (2020) presented that the metabolism of essential AA and non-essential AA such as Glu and Glutamine (Gln) in the liver decreased with the addition of sodium dichloroacetate, the sodium salt of dichloroacetic acid that shifts the metabolism of AA to the oxidation of glucose. Therefore, if nitrogen utilization and efficiency is enhanced, pig performance may be improved when pigs are fed a low CP diet. It can be concluded that perhaps one or more dispensable AA should be added to low CP diets and if the catabolism of AA in the liver is minimized, the growth performance of nursery pigs fed low CP diets could be maintained.

While pigs fed reduced CP diets experienced a linear reduction in performance, these pigs had increased fecal dry matter during the experimental period, suggesting drier and more solid feces. Nyachoti et al. (2006), Wellock et al. (2006, 2008) and Yue and Qiao (2008) concluded improved fecal consistency from a low CP diet was a result of decreased protein fermentation in the large intestine, therefore limiting the production of toxic by-products such as ammonia and amines which can increase the occurrence of gastrointestinal upsets like PWD (Pluske et al., 2002). An improvement in fecal dry matter observed in Exp. 1 was driven more by reduced CP rather than wheat bran inclusion because we did not observe a difference comparing

the negative control 21% CP diet without wheat bran to the 21% CP diet that did contain wheat bran. Molist et al. (2011) observed a decrease in the *E. coli* and coliform bacteria counts in piglet feces with the addition of 4% dietary wheat bran. Previous work by Molist et al. (2010) concluded that wheat bran decreased the ability of *E. coli* to attach to the ileum mucosa after experimental infection. Fiber addition to nursery diets has been suggested to increase the fermentation of carbohydrates while increasing the concentration of fermentation products such as butyrate, the main fuel source for colonocytes (Jensen and Jorgensen, 1994). Fiber inclusion also decreases protein fermentation (Hermes et al., 2009), while fiber may provide an alternative binding matrix for bacteria due to the carbohydrate composition being similar to intestinal receptors of enteropathogenic bacteria (Becker and Galleti, 2008). However, like the results of our study, Molist et al. (2011) concluded the addition of wheat bran did not improve growth performance.

In conclusion, pigs fed pharmacological levels of Zn had improved growth performance in Exp. 1 similar to previous studies. However, improved growth is not always observed for pigs fed high levels of Zn, similar to performance in Exp. 2. Reducing crude protein and subsequently SID Lys in diets with coarse wheat bran in an attempt to reduce the occurrence of post-weaning diarrhea did improve fecal dry matter; however, did not maintain or improve growth performance. No improvements in growth were observed for pigs fed diets supplemented with high levels of feed grade essential amino acids while improvements in feed efficiency were observed with the addition of non-essential amino acids to low crude protein diets.

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Table 1-1 Phase 1 diet composition, Exp. 1 (as-fed basis)[1]

	Control, 21% CP		CP (%) with coarse wheat bran			
	Added ZnO	No added ZnO	21	19.5	18	16.5
Ingredient, %						
Corn	44.35	44.80	41.45	45.40	48.90	52.30
Soybean meal, 46.5% CP	18.10	18.10	17.45	13.45	9.75	5.45
Dried whey	25.00	25.00	25.00	25.00	25.00	25.00
Fishmeal	4.50	4.50	4.50	4.50	4.50	4.50
Coarse wheat bran	---	---	4.00	4.00	4.00	4.00
Enzymatically treated soybean meal[2]	3.75	3.75	3.75	3.75	3.75	3.75
Soybean oil	1.50	1.50	1.50	1.50	1.50	1.50
Calcium carbonate	0.25	0.25	0.30	0.30	0.35	0.35
Monocalcium phosphate, 21% P	0.30	0.30	0.20	0.25	0.30	0.35
Salt	0.30	0.30	0.30	0.30	0.33	0.33
L-Lysine	0.43	0.43	0.44	0.47	0.49	0.56
DL-Methionine	0.23	0.23	0.22	0.21	0.20	0.21
L-Threonine	0.21	0.20	0.20	0.20	0.21	0.24
L-Tryptophan	0.07	0.07	0.07	0.08	0.08	0.10
L-Valine	0.14	0.14	0.14	0.15	0.17	0.20
L-Isoleucine	---	---	---	---	---	0.05
Trace mineral premix[3]	0.15	0.15	0.15	0.15	0.15	0.15
Vitamin premix[4]	0.25	0.25	0.25	0.25	0.25	0.25
Phytase[5]	0.08	0.08	0.08	0.08	0.08	0.08
Zinc oxide	0.40	---	---	---	---	---
Total	100	100	100	100	100	100
Calculated analysis						
Standardized digestible (SID) amino acids, %						
Lysine	1.40	1.40	1.40	1.33	1.25	1.20
Isoleucine:lysine	56	56	56	54	52	52
Leucine:lysine	109	110	108	107	106	102
Methionine:lysine	38	38	37	37	38	38
Methionine and cysteine:lysine	58	58	58	58	58	58
Threonine:lysine	65	64	64	64	64	64
Tryptophan:lysine	21.0	21.0	21.1	21.0	21.0	21.1
Valine:lysine	70	70	70	70	70	70
Total lysine, %	1.54	1.54	1.54	1.45	1.37	1.31
Metabolizable energy, kcal/kg	3,421	3,434	3,392	3,397	3,397	3,403
Net energy kcal/kg	2,578	2,589	2,552	2,574	2,594	2,620
SID lysine:net energy, g/Mcal	5.42	5.40	5.47	5.13	4.81	4.57
Crude protein, %	21.0	21.0	21.0	19.5	18.0	16.5
Calcium, %	0.65	0.65	0.65	0.65	0.66	0.66
Phosphorus, %	0.64	0.64	0.65	0.64	0.63	0.63
Available phosphorus, %	0.55	0.55	0.54	0.55	0.55	0.56

STTD P, %[6]	0.56	0.56	0.56	0.56	0.56	0.56

[1]Phase 1 diets were fed from d 0 to 7 (approximately 5.6 to 6.7 kg).

[2]HP 300 (Hamlet Protein, Findlay, OH).

[3]Provided per kg of premix: 73 g Zn from Zn sulfate; 73 g Fe from iron sulfate; 22 g Mn from manganese oxide; 11 g Cu from copper sulfate; 0.2 g I from calcium iodate; 0.2 g Se from sodium selenite.

[4]Provided per kg of premix: 3,527,399 IU vitamin A; 881,850 IU vitamin D; 17,637 IU vitamin E; 1,764 mg vitamin K; 15.4 mg vitamin B12; 33,069 mg niacin; 11,023 mg pantothenic acid; 3,307 mg riboflavin.

[5]HiPhos 2700 (DSM Nutritional Products, Parsippany, NJ) provided an estimated release of 0.10% STTD P.

[6]Standardized total tract digestible phosphorus.

Table 1-2 Phase 2 diet composition, Exp. 1 (as-fed basis)[1]

	Control, 21% CP		CP (%) with coarse wheat bran			
	Added ZnO	No added ZnO	21	19.5	18	16.5
Ingredient, %						
Corn	55.65	55.90	52.75	56.55	60.40	64.35
Soybean meal, 46.5% CP	30.20	30.15	29.35	25.30	21.30	17.00
Dried whey	10.00	10.00	10.00	10.00	10.00	10.00
Coarse wheat bran	---	---	4.00	4.00	4.00	4.00
Calcium carbonate	0.93	0.93	0.98	0.98	0.98	0.98
Monocalcium phosphate, 21% P	0.90	0.90	0.80	0.85	0.90	1.00
Salt	0.55	0.55	0.55	0.55	0.58	0.58
L-Lysine	0.47	0.47	0.48	0.58	0.61	0.68
DL-Methionine	0.22	0.22	0.21	0.23	0.23	0.23
L-Threonine	0.20	0.21	0.21	0.25	0.26	0.28
L-Tryptophan	0.06	0.06	0.06	0.08	0.08	0.10
L-Valine	0.13	0.13	0.13	0.18	0.20	0.23
L-Isoleucine	---	---	---	---	0.03	0.08
Trace mineral premix[2]	0.15	0.15	0.15	0.15	0.15	0.15
Vitamin premix[3]	0.25	0.25	0.25	0.25	0.25	0.25
Phytase[4]	0.08	0.08	0.08	0.08	0.08	0.08
Zinc oxide	0.27	---	---	---	---	---
Total	100	100	100	100	100	100
Calculated analysis						
Standardized digestible (SID) amino acids, %						
Lysine	1.35	1.35	1.35	1.33	1.25	1.20
Isoleucine:lysine	57	57	56	52	52	52
Leucine:lysine	114	114	112	106	105	101
Methionine:lysine	37	37	36	37	37	37
Methionine and cysteine:lysine	58	58	58	58	58	58
Threonine:lysine	64	64	64	64	64	64
Tryptophan:lysine	21.2	21.2	21.3	21.1	21.0	21.1
Valine:lysine	70	70	70	70	70	70
Total lysine, %	1.49	1.49	1.49	1.45	1.37	1.31
Metabolizable energy, kcal/kg	3,267	3,276	3,236	3,243	3,245	3,249
Net energy, kcal/kg	2,420	2,429	2,394	2,418	2,440	2,464
SID lysine:net energy, g/Mcal	5.57	5.55	5.63	5.47	5.11	4.86
Crude protein, %	21.0	21.0	21.0	19.5	18.0	16.5
Calcium, %	0.75	0.75	0.76	0.75	0.75	0.75
Phosphorus, %	0.62	0.62	0.63	0.62	0.61	0.61
Available phosphorus, %	0.47	0.47	0.46	0.46	0.47	0.48
STTD P, %[5]	0.51	0.51	0.51	0.51	0.51	0.51

[1]Phase 2 diets were fed from d 7 to 21 (approximately 6.7 to 10.9 kg).

[2]Provided per kg of premix: 73 g Zn from Zn sulfate; 73 g Fe from iron sulfate; 22 g Mn from manganese oxide; 11 g Cu from copper sulfate; 0.2 g I from calcium iodate; 0.2 g Se from sodium selenite.

[3]Provided per kg of premix: 3,527,399 IU vitamin A; 881,850 IU vitamin D; 17,637 IU vitamin E; 1,764 mg vitamin K; 15.4 mg vitamin B12; 33,069 mg niacin; 11,023 mg pantothenic acid; 3,307 mg riboflavin.

[4]HiPhos 2700 (DSM Nutritional Products, Parsippany, NJ) provided an estimated release of 0.10% STTD P.

[5]Standardized total tract digestible phosphorus.

Table 1-3 Phase 3 common diet composition, Exp 1. (as-fed basis)[1]

Ingredient	%
Corn	65.55
Soybean meal, 46.5% CP	30.20
Calcium carbonate	1.00
Monocalcium phosphate, 21% P	0.95
Salt	0.60
L-Lysine	0.55
DL-Methionine	0.23
L-Threonine	0.25
L-Tryptophan	0.08
L-Valine	0.15
Trace mineral premix[2]	0.15
Vitamin premix[3]	0.25
Phytase[4]	0.08
Total	100
Calculated analysis	
Standardized digestible (SID) amino acids, %	
Lysine	1.35
Isoleucine:lysine	54
Leucine:lysine	112
Methionine:lysine	37
Methionine and cysteine:lysine	58
Threonine:lysine	64
Tryptophan:lysine	21.3
Valine:lysine	70
Total lysine, %	1.49
Metabolizable energy, kcal/kg	3,271
Net energy, kcal/kg	2,422
SID lysine:net energy, g/Mcal	5.56
Crude protein, %	20.8
Calcium, %	0.73
Phosphorus, %	0.59
Available phosphorus, %	0.42
STTD P, %[5]	0.46

[1]A common diet were fed from d 21 to 45, (approximately 10.9 to 25.9 kg).

[2]Provided per kg of premix: 73 g Zn from Zn sulfate; 73 g Fe from iron sulfate; 22 g Mn from manganese oxide; 11 g Cu from copper sulfate; 0.2 g I from calcium iodate; 0.2 g Se from sodium selenite.

[3]Provided per kg of premix: 3,527,399 IU vitamin A; 881,850 IU vitamin D; 17,637 IU vitamin E; 1,764 mg vitamin K; 15.4 mg vitamin B12; 33,069 mg niacin; 11,023 mg pantothenic acid; 3,307 mg riboflavin.

[4]HiPhos 2700 (DSM Nutritional Products, Parsippany, NJ) provided an estimated release of 0.10% STTD P.

[5]Standardized total tract digestible phosphorus.

Table 1-4 Diet composition, Exp. 2 (as-fed basis)[1]

	21% CP		18% CP, no ZnO		
Ingredient, %	ZnO	No ZnO	1.2% Lysine	1.35% Lysine	1.35% Lysine + NEAA
Corn	53.15	53.45	60.55	60.00	57.60
Soybean meal, 46.5% CP	28.75	28.70	21.35	21.25	21.40
Dried whey	10.00	10.00	10.00	10.00	10.00
Coarse wheat bran	4.00	4.00	4.00	4.00	4.00
Calcium carbonate	0.95	0.95	0.95	0.95	0.95
Monocalcium phosphate, 21% P	0.80	0.80	0.90	0.90	0.90
Salt	0.55	0.55	0.55	0.55	0.55
L-Lysine	0.50	0.50	0.54	0.74	0.74
DL-Methionine	0.20	0.20	0.23	0.31	0.31
L-Threonine	0.24	0.24	0.24	0.34	0.34
L-Tryptophan	0.03	0.03	0.07	0.11	0.11
L-Valine	0.10	0.10	0.17	0.27	0.27
L-Isoleucine	---	---	---	0.13	0.13
L-Histidine	---	---	---	0.04	0.04
Trace mineral premix[2]	0.15	0.15	0.15	0.15	0.15
Vitamin premix[3]	0.25	0.25	0.25	0.25	0.25
Phytase[4]	0.08	0.08	0.08	0.08	0.08
Zinc oxide	0.25	---	---	---	---
Glycine	---	---	---	---	1.10
Glutamic acid	---	---	---	---	1.10
Total	100	100	100	100	100
Calculated analysis					
Standardized digestible (SID) amino acids, %					
Lysine	1.35	1.35	1.20	1.35	1.35
Isoleucine:lysine	55	55	52	55	55
Leucine:lysine	110	111	110	97	96
Methionine:lysine	35	35	39	40	40
Methionine and cysteine:lysine	57	57	61	60	59
Threonine:lysine	65	65	65	65	65
Tryptophan:lysine	18.9	18.9	21.0	21.1	21.1
Valine:lysine	67	67	70	70	69
Histidine:lysine	35	35	33	32	32
Total lysine, %	1.49	1.49	1.32	1.47	1.47
Metabolizable energy, kcal/kg	3,227	3,236	3,245	3,254	3,247
Net energy, kcal/kg	2,389	2,396	2,440	2,446	2,440
SID lysine:net energy, g/Mcal	5.64	5.62	4.91	5.51	5.52
Crude protein, %	20.7	20.7	17.9	18.3	20.1
Calcium, %	0.75	0.75	0.75	0.75	0.75
Phosphorus, %	0.62	0.62	0.61	0.61	0.60
Available phosphorus, %	0.46	0.46	0.47	0.47	0.47

STTD P, %[5]	0.51	0.51	0.51	0.51	0.50

[1]Experimental diets were fed from approximately d 0 to 13 (7.0 to 11.7 kg in Exp. 2, and 6.2 to 11.9 kg in Exp. 3.

[2]Provided per kg of premix: 73 g Zn from Zn sulfate; 73 g Fe from iron sulfate; 22 g Mn from manganese oxide; 11 g Cu from copper sulfate; 0.2 g I from calcium iodate; 0.2 g Se from sodium selenite.

[3]Provided per kg of premix: 3,527,399 IU vitamin A; 881,850 IU vitamin D; 17,637 IU vitamin E; 1,764 mg vitamin K; 15.4 mg vitamin B12; 33,069 mg niacin; 11,023 mg pantothenic acid; 3,307 mg riboflavin.

[4]HiPhos 2700 (DSM Nutritional Products, Parsippany, NJ) provided an estimated release of 0.10% STTD P.

[5]Standardized total tract digestible phosphorus.

Table 1-5 Phase 3 common diet composition, Exp. 2 (as-fed basis)[1]

Ingredient	%
Corn	65.47
Soybean meal, 46.8% CP	28.30
Choice white grease	2.00
Calcium carbonate	0.75
Monocalcium phosphate, 21% P	1.10
Sodium chloride	0.60
L-Lysine-HCl	0.55
DL-Methionine	0.25
L-Threonine	0.23
L-Tryptophan	0.05
L-Valine	0.16
Trace mineral premix[2]	0.15
Vitamin premix with phytase[3]	0.25
Pellet stabilizer[4]	0.15
Total	100
Calculated analysis	
Standardized digestible (SID) amino acids, %	
Lysine	1.30
Isoleucine:lysine	53
Leucine:lysine	111
Methionine:lysine	39
Met and cysteine:lysine	60
Threonine:lysine	63
Tryptophan:lysine	19.3
Valine:lysine	70
Histidine:lysine	35
Total Lysine, %	1.41
Metabolizable energy, kcal/kg	3,318
Net energy, kcal/kg	2,534
Crude protein, %	19.9
Calcium, %	0.65
Available phosphorus, %	0.42
STTD P[5], %	0.48

[1]Phase 3 common diets were fed only to group 2 from d 13 to 27.

[2]Provided per kg of premix: 73 g Zn from Zn sulfate; 73 g Fe from iron sulfate; 22 g Mn from manganese oxide; 11 g Cu from copper sulfate; 0.2 g I from calcium iodate; 0.2 g Se from sodium selenite.

[3]Ronozyme HiPhos GT 2700 (DSM Nutritional Products, Parsippany, NJ) provided an expected P release of 0.10%. Provided per kg of premix: 3,527,399 IU vitamin A; 881,850 IU vitamin D; 17,637 IU vitamin E; 1,764 mg vitamin K; 15.4 mg vitamin B12; 33,069 mg niacin; 11,023 mg pantothenic acid; 3,307 mg riboflavin.

[4]Alltech All-Bind HD (Alltech, Nicholasville, KY).

[5]STTD P = standardized total tract digestible phosphorus.

Table 1-6 Analyzed diet composition Exp 1. (as-fed basis)[1,2]

	Control, 21% CP		CP (%) with coarse wheat bran[3]			
Analyzed composition	Added ZnO	No added ZnO	21	19.5	18	16.5
Phase 1						
Dry matter, %	91.1	91.0	91.0	91.1	90.9	90.8
Crude fiber, %	1.6	1.6	2.2	2.1	1.9	2.4
Acid detergent fiber, %	2.1	2.3	2.7	2.8	2.6	2.4
Neutral detergent fiber, %	4.6	4.6	6.0	5.9	5.6	5.6
Crude protein, %	20.3	20.3	20.6	18.6	17.2	15.7
Zn, mg/kg	2,526	164	126	169	125	145
Ca, %	0.89	0.91	0.91	0.86	0.88	0.97
P, %	0.61	0.64	0.63	0.61	0.62	0.60
Phase 2						
Dry matter, %	89.2	89.0	89.2	88.9	89.1	89.1
Crude fiber, %	2.1	2.1	2.3	2.1	2.0	2.1
Acid detergent fiber, %	3.1	2.7	3.1	3.3	3.0	2.6
Neutral detergent fiber, %	6.1	6.0	7.2	6.9	6.6	6.2
Crude protein, %	20.8	20.3	21.0	20.3	17.9	15.7
Zn, mg/kg	1,575	105	187	115	153	156
Ca, %	0.90	0.97	0.88	0.79	0.88	0.93
P, %	0.57	0.58	0.61	0.60	0.59	0.58

[1]Diets were fed in 2 phases from d 0 to 7 and d 7 to 21, for phases 1 and 2, respectively.

[2]Complete diet samples were taken at manufacturing. Samples were stored at -20°C until they were homogenized and subsampled. Duplicate samples per treatment were submitted for analysis (Ward Laboratories, Inc., Kearney, NE).

[3]Coarse wheat bran was included in the diet at 4% from d 0 to d 21.

Table 1-7 Effect of crude protein level with coarse wheat bran on growth performance of nursery pigs, Exp. 1[1]

	Control, 21% CP		CP (%) with coarse wheat bran					Probability, *P* =				
								CP level		ZnO	+ Control vs. 21%	- Control vs. 21%
Item	Added ZnO[2]	No added ZnO[2]	21	19.5	18	16.5	SEM	Linear	Quadratic	+ vs. -	CP	CP
BW, kg												
d 0	5.6	5.6	5.6	5.6	5.6	5.6	0.15	0.202	0.461	0.954	0.908	0.862
d 7	6.9	6.8	6.8	6.7	6.6	6.6	0.18	0.001	0.275	0.256	0.572	0.565
d 21	12.2	10.8	10.9	10.9	10.3	10.3	0.56	0.003	0.957	< 0.001	< 0.001	0.709
d 45	26.9	26.0	26.3	25.9	25.5	25.2	0.66	0.010	0.751	0.056	0.236	0.454
d 0 to 7												
ADG, g	177	165	171	154	135	136	7.4	< 0.001	0.226	0.258	0.557	0.585
ADFI, g	171	169	168	169	155	161	8.8	0.158	0.703	0.747	0.653	0.899
G:F, g/kg	1,031	977	1,021	910	868	846	37.9	< 0.001	0.141	0.206	0.816	0.300
d 7 to 21												
ADG, g	383	290	294	295	266	262	27.7	0.017	0.823	< 0.001	< 0.001	0.813
ADFI, g	467	382	395	399	363	377	19.3	0.102	0.705	< 0.001	< 0.001	0.478
G:F, g/kg	818	753	743	737	732	698	37.2	0.048	0.371	0.005	0.001	0.643
Experimental period (d 0 to 21)												
ADG, g	314	248	253	247	222	220	19.3	0.002	0.830	< 0.001	< 0.001	0.711
ADFI, g	369	311	319	322	293	304	15.2	0.065	0.634	< 0.001	< 0.001	0.531
G:F, g/kg	851	795	792	767	757	724	27.0	0.002	0.785	0.007	0.005	0.887
Post-test period (d 21 to 45)[3]												
ADG, g	611	624	640	625	632	622	9.2	0.263	0.788	0.338	0.033	0.228
ADFI, g	951	928	964	941	929	924	19.6	0.058	0.565	0.281	0.572	0.103
G:F, g/kg	643	673	664	666	680	674	9.7	0.078	0.491	< 0.001	0.007	0.284
d 0 to 45												
ADG, g	473	448	457	448	440	433	11.1	0.012	0.838	0.014	0.124	0.331
ADFI, g	680	639	660	651	631	633	16.6	0.038	0.606	0.008	0.187	0.164
G:F, g/kg	696	701	693	689	697	685	4.8	0.443	0.410	0.468	0.701	0.269

[1]A total of 360 pigs (Line 200 × 400, DNA, Columbus, NE initially 5.6 kg) were used in a 45-d growth study with 5 pigs per pen and 12 pens per treatment. ADG = average daily gain. ADFI = average daily feed intake. G:F = feed efficiency.

[2]ZnO was included in the diet to provide 3,000 mg/kg of Zn from d 0 to 7; 2,000 mg/kg of Zn from d 7 to 21; and no additional Zn other than that from the trace mineral premix (110 mg/kg Zn) from d 21 to 45. The negative control diet contained 110 mg/kg added Zn from the premix for the entire study.

[3]A common diet was fed from d 21 to 45.

Table 1-8 Effect of crude protein level with coarse wheat bran in nursery pig diets on fecal dry matter, %, Exp. 1[1]

								Probability, *P* =				
	Control, 21% CP		CP (%) with coarse wheat bran					CP level		ZnO	+ Control vs. 21%	- Control vs. 21%
Item	Added ZnO[2]	No added ZnO[2]	21	19.5	18	16.5	SEM	Linear	Quadratic	+ vs -	CP	CP
Day of collection[3]												
d 7	28.8	26.8	26.5	27.7	29.3	28.9	0.88	0.029	0.349	0.108	0.059	0.776
d 21	21.7	20.8	21.3	23.2	24.4	24.4	0.84	0.006	0.282	0.488	0.779	0.679
d 45	24.1	27.0	26.5	24.9	24.0	23.5	0.70	0.002	0.433	0.004	0.016	0.631

[1]Values represent the mean of 3 pigs per pen and 12 pens per treatment. Three pigs per pen were randomly selected and sampled. Fecal samples were then pooled by pen respective of day of collection and dried at 55°C in a forced air oven

[2]ZnO was included in the diet to provide 3,000 mg/kg of Zn from d 0 to 7; 2,000 mg/kg of Zn from d 7 to 21; and no additional Zn other than that from the trace mineral premix (110 mg/kg Zn) from d 21 to 45. The negative control diet contained 110 mg/kg added Zn from the premix for the entire study.

[3]Experimental diets were fed from d 0 to 21 and a common diet was fed from d 21 to 45.

Table 1-9 Analyzed diet composition Exp. 2 (as-fed basis)[1,2]

	21% CP		18% CP, no ZnO		
Analyzed composition	ZnO	No ZnO	1.2% Lysine	1.35% Lysine	1.35% Lysine + NEAA
Exp 2. Group 1					
Dry matter, %	92.8	89.9	90.2	90.2	89.9
Crude fiber, %	1.8	2.1	1.5	1.8	1.9
Acid detergent fiber, %	4.1	4.0	3.2	3.4	3.6
Neutral detergent fiber, %	8.7	9.9	7.7	7.9	7.9
Crude protein, %	21.3	21.5	17.6	18.2	19.9[4]
Zn, mg/kg	1,377	130	168	121	100
Ca, %	0.82	0.62	0.76	0.69	0.58
P, %	0.58	0.57	0.53	0.52	0.50
Exp. 2 Group 2					
Dry matter, %	90.1	89.6	89.6	89.5	90.0
Crude fiber, %	2.8	2.9	3.0	2.4	2.6
Acid detergent fiber, %	4.5	5.1	4.8	3.6	3.5
Neutral detergent fiber, %	11.4	10.4	12.1	8.9	8.6
Crude protein, %	20.9	21.0	18.2	18.0	20.2[3]
Zn, mg/kg	1,523	140	112	187	113
Ca, %	0.74	0.80	0.68	0.83	0.82
P, %	0.53	0.55	0.60	0.56	0.69

[1] In Exp. 2 group 1 diets were fed from d 0 to 13, and in Exp. 2 group 2, experimental diets were fed from d 0 to 13 and all pigs received the same common diet from d 13 to 27.

[2]Complete diet samples were taken at manufacture. Samples were stored at -20°C until they were homogenized and subsampled. Duplicate samples per treatment were submitted for analysis to (Ward Laboratories, Inc., Kearney, NE).

[3]Crude protein greater than 18% is observed due to the nitrogen from the nonessential amino acids added to the diet.

Table 1-10 Effect of coarse wheat bran and reducing dietary CP content with supplemented essential or non-essential amino acids on nursery pig performance, Exp. 2[1]

	21% CP[2]		18% CP, No ZnO			
Item	ZnO	No ZnO	1.2% Lysine[3]	1.35% Lysine[4]	1.35% Lysine + NEAA[5]	SEM
BW, kg						
d 0	6.6	6.6	6.6	6.6	6.6	0.11
d 13	12.3[a]	12.0[ab]	11.7[bc]	11.6[c]	11.7[bc]	0.18
d 0 to 13 (Experimental period)						
ADG, g	429[a]	417[ab]	386[bc]	378[c]	393[abc]	12.2
ADFI, g	598	586	601	592	565	17.2
G:F, g/kg	719[a]	713[a]	642[b]	640[b]	695[a]	10.1
d 13 to 27 (Common period)[6]						
ADG, g	597	618	598	603	594	14.6
ADFI, g	891	925	906	899	904	20.0
G:F, g/kg	668	669	660	673	658	9.3

[abc] Means in the same row with different superscripts differ ($P < 0.05$).

[1]A total of 650 pigs (Line 241 × 600, DNA, Columbus, NE, initial BW of 6.6 kg) were used in a 13-d growth study with 5 pigs per pen and 26 pens per treatment. All diets contained 4% coarse wheat bran. After weaning, pigs were fed a common starter diet until d 10 or 14 post-weaning for group 1 and 2, respectively, which was considered d 0 of the trial.

[2]Diets were formulated to 21% CP (1.35% SID Lys) with or without pharmacological levels of ZnO (2,000 mg/kg).

[3]Treatment diet was formulated to 18% CP and 1.2% SID Lysine by adding feed grade amino acids until the minimum Ile:Lys requirement of 52% was met.

[4]Treatment diet was formulated to 18% CP and 1.35% SID Lys with high amounts of feed grade amino acids. L-Ile and L-His were added along with other feed grade amino acids.

[5]Treatment diet was formulated to 18% CP and 1.35% SID Lys with high amounts of feed grade amino acids and with the addition of non-essential amino acids (glycine and glutamic acid).

[6]A common diet was fed only to group 2 with 14 pens per treatment.

Table 1-11 Effect of coarse wheat bran and reducing dietary CP content with supplemented essential or non-essential amino acids in nursery pig diets on fecal dry matter, %, Exp. 2[1]

	21% CP[2]		18% CP, no ZnO			
Item	ZnO	No ZnO	1.2% Lysine[3]	1.35% Lysine[4]	1.35% Lysine + NEAA[5]	SEM
Day of collection						
d 0	23.1	24.4	23.5	23.2	23.2	0.67
d 6[6]	16.7[b]	16.4[b]	18.9[a]	17.0[ab]	18.0[ab]	0.58
d 13	18.0[ab]	17.2[b]	19.2[a]	18.1[ab]	18.2[ab]	0.51
d 20[7]	21.9	23.4	21.2	21.3	22.0	0.83
d 27[7]	20.9	23.0	21.5	22.8	20.8	0.94

[ab]Means in the same row with different superscripts differ ($P < 0.05$).

[1]Values represent the mean of 3 pigs per pen and 26 pens per treatment. Three pigs per pen were randomly selected and sampled. Fecal samples were then pooled by pen respective of day of collection and dried at 55°C in a forced air oven

[2]Diets were formulated to 21% CP with or without pharmacological levels of ZnO (2,000 mg/kg).

[3]Treatment diet was formulated to 18% CP and 1.2% SID Lysine by adding feed grade amino acids until the minimum Ile:Lys requirement of 52% was met.

[4]Treatment diet was formulated to 18% CP and 1.35% SID Lys with high amounts of feed grade amino acids. L-Ile and L-His were added along with other feed grade amino acids.

[5]Treatment diet was formulated to 18% CP and 1.35% SID Lys with high amounts of feed grade amino acids and with the addition of non-essential amino acids (glycine and glutamic acid).

[6]Group 1 samples were collected on d 7 and group 2 on collected on d 6 of each trial.

[7]Collection days consist of 3 pigs per pen and 14 pens per treatment. These collection days were only done for group 2 in the post-treatment period from d 13 to 27.

Chapter 2 - Effect of fiber source and crude protein level on nursery pig performance

Abstract

Post-weaning diarrhea is a common gastrointestinal condition that impacts newly weaned pigs. Reduction in dietary crude protein and addition of fiber to nursery diets could mitigate the severity of this issue. Therefore, a total of 360 pigs (Line 200 × 400, DNA, Columbus, NE, initially 5.0 kg) were used in a 45-d growth trial to evaluate the effects of fiber source and crude protein on growth performance and fecal dry matter of nursery pigs. Upon arrival to the nursery research facility, pigs were randomly assigned to pens and allotted to 1 of 8 dietary treatments with 5 pigs per pen and 9 replicate pens per treatment. Dietary treatments were arranged in a 2 × 4 completely randomized factorial with main effects of crude protein (21 or 18% CP) and fiber source (none, coarse wheat bran, oat hulls, or cellulose). Treatment diets were formulated in two dietary phases from d 0 to 10 and 10 to 24, with a common post-treatment diet fed from 24 to 45. The 21% CP diets contained 1.40% standardized ileal digestible (SID) Lys in phase 1 and 1.35% SID Lys in phase 2. Standardized ileal digestible lysine was lowered in order to reduce crude protein level for the 18% CP diets to limit amino acid deficiencies relative to lysine. Therefore, the 18% CP diets contained 1.25% SID Lys in both phases. Diets containing a fiber source were formulated to the level of insoluble fiber provided by 4% coarse wheat bran, resulting in the addition of 1.85% oat hulls and 1.55% cellulose to the corresponding diets. No fiber source × CP level interactions ($P > 0.05$) were observed throughout the study. Decreasing dietary CP (and subsequently SID lysine) decreased ($P = 0.05$) ADG, G:F, and d 24 BW during the experimental period. From d 0 to 45, ADG and d 45 BW decreased ($P = 0.05$) for pigs fed 18% CP diets compared to pigs fed 21% CP. No main effects of fiber source were observed for growth

performance. Fecal dry matter on d 17 was increased ($P < 0.001$) for pigs fed 18% CP diets compared to pigs fed 21% CP diets. Pigs fed diets with added cellulose had increased ($P < 0.05$) fecal dry matter during the experimental period compared to pigs fed no fiber source or wheat bran. In conclusion, reducing crude protein (and subsequently SID Lys) decreased growth performance. The source or inclusion of dietary fiber in nursery diets had no impact on growth performance; however, the inclusion of cellulose in nursery diets improved fecal dry matter.

Key Words: crude protein, fecal dry matter, growth, insoluble fiber, nursery pig

Introduction

Post-weaning diarrhea is a condition that affects weanling pigs during the first 2 weeks after weaning and is determined by recurrent discharge of loose, watery feces (Rhouma et al., 2017). This condition presents a major economic burden to the swine industry as pigs experience diminished growth, dehydration, reduced nutrient digestibility, and death can occur in severe cases (Heo et al., 2012). In recent years, regulatory restrictions and bans on industry accepted mitigants of PWD and growth promoters such as pharmacological Zinc and antimicrobial substances pose as a setback to pig health and performance in commercial production settings (Brugger and Windisch, 2017). An alternative dietary strategy to minimize the negative effects of PWD and intestinal upsets while maintaining pig performance is needed; however, is yet to be determined.

Young pigs struggle to digest certain plant-derived protein sources due to underdeveloped proteolytic enzymes. Therefore, it has become an accepted practice to include highly digestible protein sources in nursery diets (Williams, 2003) with the corresponding level of dietary crude protein typically ranging from 21 to 25% CP (Pluske et al., 2002). Not all

dietary proteins are digested and absorbed by the pig, as 20 to 40% of consumed protein escapes the small intestine. As a result, undigested protein in the large intestine serves as a substrate for bacterial fermentation increasing the production of compounds such as ammonia, amines, branched fatty acids, phenols, and indoles which consequently have toxic effects on the pig and can impact microbiota diversity (Halas et al., 2007). Promoting commensal microbiota populations in the gastrointestinal tract of pigs has been identified as one of the most important risk factors for PWD (Jeaurond et al., 2008). Enterotoxigenic strains of *Escherichia coli* (*E. coli*) prefer to ferment protein, therefore the modification of dietary CP has been suggested as a method to reduce piglet scouring. Several studies have concluded that reducing the dietary crude protein (CP) level in diets will improve the fecal consistency of pigs (Nyachoti et al., 2006; Wang et al., 2018; Yue and Qiao, 2008) and decrease the severity of PWD in pigs challenged with *E. coli* (Opapeju et al., 2015).

Fiber can be used in nursery diets for the amelioration of PWD, while insoluble fiber is preferred in post-weaning diets to increase digesta passage rate and to prevent the colonization of pathogenic bacteria (McDonald et al., 2001). Cellulose is the most abundant source of insoluble fiber as it is the primary structural polysaccharide in plant cell walls and acts as a hydrophilic bulking agent for pig feces (Chen et al., 2020) Coarse wheat bran and oat hulls have been categorized as feedstuffs with high insoluble fiber content (Jha and Berrocoso, 2015). Purified cellulose, coarse wheat bran, and oat hulls are common insoluble fiber ingredients used in post-weaning diets (Molist et al., 2014). Supplementing 1.5% purified cellulose reduced the incidence of diarrhea in newly weaned pigs as the adherence sites of pathogenic bacteria were proposed to have been blocked by the inclusion of cellulose (Pascoal et al., 2012). Molist et al. (2009) fed 7.4 kg pigs either a diet with added 4% wheat bran, 3% sugar beet pulp, or a combination of wheat

bran and sugar beet pulp and concluded that pigs fed wheat bran had increased feed intake compared to pigs fed a control diet. Pigs challenged with *E. coli* $K88^+$ and fed 4% coarse wheat bran had decreased cases of diarrhea due to the reduced ability of *E. coli* adhesion to the intestine (Molist et al., 2010). Similarly, Mateos et al. (2006) concluded that adding either 2 or 4% of oat hulls to a corn or rice-based diet reduced the incidence of diarrhea, while Mateos et al. (2007) observed that the inclusion of 2% oat hulls had no effect on pig performance.

Diet composition modification to reduce crude protein and with the inclusion of insoluble fiber are a means suggested to stabilize microbiota populations (Konstantinov et al., 2003). This would also normalize the balance of commensal and pathogenic bacteria in the gastrointestinal tract consequently reducing susceptibility to enteric disorders, which could improve pig performance. Therefore, the objective of this study was to determine the effect of dietary crude protein with and without the inclusion of a fiber source on nursery pig performance and fecal dry matter.

Materials and Methods

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment. The study was conducted at the Kansas State University Segregated Early Weaning Facility in Manhattan, KS. Each pen contained a 4-hole, dry self-feeder and cup waterer for ad libitum access to feed and water.

A total of 360 barrows (Line 200 × 400, DNA, Columbus, NE, initially 5.0 kg) were used in a 45-d growth trial. Pigs were weaned at approximately 21 d of age and, following arrival to the research facility, were randomized to pens and allotted to 1 of 8 dietary treatments with 5 pigs per pen and 9 pens per treatment. Treatments were equally represented in each of the 2 barns, with 4 replications and 5 replications in barn 1 and 2, respectively. Dietary treatments

were arranged in a 2 × 4 factorial with the main effects of crude protein (CP; 21 or 18%) and fiber source (none, 4% coarse wheat bran, 1.85% oat hulls, or 1.55% cellulose; Arbocel, J. Rettenmaier USA, Schoolcraft, MI). The diets with 21% CP contained 1.40% standardized ileal digestible (SID) Lys in phase 1 and 1.35% SID Lys in phase 2, while the 18% CP diets contained 1.25% SID Lys in both phases. Diets were formulated to a maximum SID Lys:digestible CP level of 6.35% as suggested by Millet et al. (2018) to sustain an acceptable amount of nitrogen for non-essential amino acid synthesis, thus SID Lys decreased in the 18% CP diets to maintain the Lys:digestible CP ratio. All diets were formulated to obtain a similar ratio of essential SID amino acids to SID Lys by using feed grade amino acids. Prior to the start of the trial, coarse wheat bran, oat hulls, and cellulose were analyzed (University of Illinois, Urbana-Champaign, IL) for ADF, NDF, insoluble, soluble, and total dietary fiber (Table 2-1). These values were used in diet formulation to provide a similar amount of insoluble fiber in all diets that contained the fiber sources using the inclusion of 4% coarse wheat bran as the target for insoluble fiber content. The addition of the fiber sources to obtain the same insoluble fiber content as 4% coarse wheat bran to the high and low CP diets increased insoluble fiber content of the diet by 1.4 percentage units compared with the control diet. The inclusion of 4% coarse wheat bran was selected from previous research (Batson, unpublished data) based on work by Molist et al. (2010, 2011) concluding that 4% coarse wheat bran had no negative impacts on nursery pig performance, as high-fiber diets can adversely affect energy and nutrient utilization (Wenk, 2001). Treatment diets were offered in two dietary phases (phase 1 fed from d 0 to 10 and phase 2 from d 10 to 24 post-weaning; Tables 2-2 and 2-3). A post-treatment period with a common diet containing 19.9% CP and 7.5% insoluble fiber was fed from d 24 to 45 (Table 2-4).

Ingredient nutrient values as well as their SID coefficients used in diet formulation were derived from NRC (2012).

All dietary treatments were manufactured at the Kansas State University Tom Avery Poultry Research farm in Manhattan, KS and were corn-soybean meal-based. The average particle size of coarse wheat bran, oat hulls, and cellulose included in experimental diets were 1,041, 1,168, and 101 microns, respectively. Particle size analysis was done using the ANSI/ASAE S319.2 method with a Ro-tap 13-sieve Shaker using flow agent and sieve agitators as recommended by Kalivoda et al. (2017). The first phase was fed in pelleted form and the second phase was fed in meal form. The common post-treatment diet was offered in pelleted form. Samples of complete diets were collected during bagging of experimental diets with a subsample collected from every third bag and pooled into one homogenized sample per dietary treatment. Samples were stored at -20°C until they were subsampled and submitted for analysis (Ward Laboratories, Kearney, NE) for dry matter (method 935.29; AOAC International, 2019), CP (method 990.03; AOAC International, 2019), ADF (ANKOM Technology, 1998), crude fiber (ANKOM Technology, 2005), and NDF (ANKOM Technology, 2017).

Pigs and feeders were weighed to determine ADG, ADFI, and G:F on d 10, 17, 24, and 45 of the study. Fecal samples were collected from the same three pigs per pen on d 10, 17, 24, and 45 of the study. Fecal samples were collected into clean, single use zipper storage bags and stored at -20°C until fecal dry matter analysis. Fecal samples were pooled by pen respective of day of collection and dried for 48 h at 55°C in a forced air oven. Fecal dry matter was determined as follows: (dried sample weight at 48 h – pan weight) / (initial wet sample weight – pan weight) × 100.

Data were analyzed as a completely randomized design in a 2 × 4 factorial arrangement. The lmer function was used from the lme4 package in R (version 3.6.1 (2019-07-05), R Foundation for Statistical Computing, Vienna, Austria), with pen serving as the experimental unit. Barn was included in the model statement as a random effect and treatment as a fixed effect. The main effects of CP level and fiber source, as well as their interactions, were tested. A repeated measures statement, with the random effect of barn, was used for analyzing fecal dry matter. Differences between treatments were considered significant at $P \leq 0.05$ and marginally significant at $0.05 < P \leq 0.10$.

Results

Results of chemical analysis of experimental diets were consistent with formulation (Table 2-5), however; analyzed CP were slightly lower than formulated.

For growth measurements no CP × fiber source interactions were observed throughout the 45-d study (Table 2-6). From d 0 to 10, pigs fed 21% CP had increased ($P < 0.05$) ADG, d 10 BW, and G:F compared to pigs fed diets with 18% CP (Table 2-7). Similar responses to dietary CP level were observed from d 10 to 24, as pigs fed 18% CP diets had decreased ($P = 0.020$) ADG and poorer ($P = 0.023$) G:F compared to pigs fed 21% CP diets. No evidence for differences for growth performance were observed among any of the fiber sources in phase 1 and 2.

For the overall experimental phase (d 0 to 24), pigs fed 21% CP diets had improved ($P < 0.05$) ADG and G:F compared to pigs fed 18% CP diets. An increase in performance for pigs fed 21% CP resulted in heavier ($P = 0.002$) BW on d 24 compared to pigs fed 18% CP diets. A post-treatment common diet was fed from d 24 to 45, and no evidence for difference in any growth criteria for previously fed CP level or fiber source was observed. Overall (d 0 to 45), pigs fed

21% CP diets had increased ($P < 0.05$) ADG and final BW at the end of the study compared to pigs fed 18% CP diets. Fiber source had no effect on nursery pig growth performance.

For fecal dry matter (DM) percentage, no CP level × fiber source interactions were observed (Table 2-8). Fecal DM was increased ($P < 0.006$) on d 10 and 24 for pigs fed diets with added cellulose compared to those fed diets with no fiber or pigs fed diets containing wheat bran with pigs fed oat hulls intermediate (Table 2-9). No evidence for differences in fecal DM on d 45 were observed between pigs previously fed 21 or 18% CP or between pigs fed diets with or without any fiber source from d 0 to 24.

Discussion

Pigs fed low CP diets supplemented with crystalline amino acids have a lower instance and severity of diarrhea (Heo et al. 2008, 2009; Pierce et al., 2007; Opapeju et al. 2008; Yue and Qiao 2008). It has also been observed for pigs fed low CP diets to have increased firmness of feces and more solid stool when pigs were challenged with K88, a strain of *Escherichia coli* known to initiate PWD (Opapeju et al., 2009; Wellock et al., 2008). Pigs fed low CP diets have greater resistance to gastrointestinal infections compared to pigs fed higher dietary levels of CP (Houdijk et al., 2007). These responses are believed to be attributed to a decrease in the amount of undigested nutrients entering the large intestine. High levels of undigested nutrients would act as a substrate for microbial fermentation and promote the development of pathogenic microflora. Low CP diets increase the production of short-chain fatty acids which aid in the establishment of commensal microbial populations (Williams et al., 2001) while also reducing inflammatory responses linked to pathogenic infection (Opapeju et al., 2009). Stein and Kil (2006) state that reducing dietary CP is the single most effective method to reduce piglet scours. In the present study, fecal dry matter was used to evaluate treatment effects on the incidence of scours. Pigs fed

diets with 18% CP had greater fecal dry matter percentage (21.1 versus 23.9%) compared to pigs fed 21% CP diets on d 17 of the experiment. In support of these findings, Heo et al. (2009) observed an increase in fecal dry matter for pigs fed diets with 17.5% CP compared to pigs fed diets with 25.6% CP. Although not statistically significant, pigs fed 18% CP diets had a numerically higher fecal dry matter during the experimental phase on d 10 and 24 compared to pigs fed diets with 21% CP.

Reducing dietary CP level has been presented to cause mixed results regarding nursery pig growth performance. In this study, a decrease in ADG and G:F was observed consistently throughout the experiment for pigs fed the 18% CP diets with subsequently lower SID Lys compared to pigs fed 21% CP diets, resulting in a 0.7 kg decrease in final BW for pigs fed 18% CP diets. The results from the present study are in agreement with Wellock et al. (2006), as the authors observed decreased growth performance when dietary CP was reduced from 23 to 18% CP, where SID Lys levels differed between treatments. Nyachoti et al. (2006) and Opapeju et al. (2008) fed diets with dietary CP ranging from 21 to 17% CP supplemented with crystalline amino acids, however Nyachoti et al. (2006) maintained 1.40% SID Lys across all treatments and Opapeju et al. (2008) maintained SID Lys at 1.35%. Decreased performance was observed for pigs fed at or lower than 19% CP (Nyachoti et al., 2006) and reduced growth was also observed by Opapeju et al. (2008) for pigs fed decreasing dietary CP. Reductions in dietary CP may be limited by diet histidine levels or unknown requirements for the next-limiting amino acid either indispensable or dispensable. In contrast, results presented by Reynoso et al. (2004) found that dietary CP level could be reduced from 21.2 to 18.4% with no reductions in growth performance. Le Bellego and Noblet (2002) and Heo et al. (2008) observed a similar response as CP level had no effect on performance of 12 kg and 6.1 kg pigs, respectively. The CP content

evaluated by Htoo et al. (2007) were 20 and 24% CP for the low and high CP diets respectively, and no differences in performance were also observed. Contradicting results observed by comparing studies with dietary CP reductions could be attributed to differences in weaning age, initial BW, and the dietary CP content classified as low or high, or if SID Lys was balanced across treatment diets. In the present study, decreased growth for pigs fed 18% CP diets is believed to be driven by a SID Lys deficiency while all diets contained a similar ratio of SID essential amino acids to SID Lys. Diets were formulated to a maximum SID Lys:digestible CP level of 6.35% as suggested by Millet et al. (2018) to sustain an acceptable amount of nitrogen for non-essential amino acid synthesis, thus SID Lys decreased in the 18% CP diets to maintain the Lys:digestible CP ratio.

In the present study, a common diet with adequate CP to optimize growth was fed from d 24 to 45. Pigs previously fed 18% CP had similar performance to that of pigs previously fed 21% CP diets. Previous studies have indicated that feeding a diet with adequate CP and amino acid levels after a period of deficiency enables pigs to compensate for reduced growth during the immediate postweaning period (Kyriazakis et al. 1991). Stein and Kil (2006) support this statement by concluding that pigs fed a low protein diet for 2 weeks postweaning can achieve similar overall performance when the next diet offered contains adequate levels of CP. In contrast, pigs in our experiment did not compensate as overall ADG was lower for pigs fed 18% CP diets, therefore resulting in lower final BW at the conclusion of the trial. It is suggested that the restriction period length and the degree of amino acid restriction pigs are subjected to could determine the compensatory gain response (Kamalakar et al., 2009). A review conducted by Menegat et al. (2020) also states that the degree of Lys restriction and the duration of the

restriction and recovery periods pigs are subjected to are key factors determining the compensatory growth response of grow-finish pigs.

Plant carbohydrates are classified as sugars, disaccharides, oligosaccharides or polysaccharides, where non-starch polysaccharides (NSP) and lignin are the main components of plant cell walls and are also called dietary fiber (Agyekum and Nyachoti, 2017). Fiber is defined as any plant carbohydrate that is resistant to enzymatic hydrolysis in the digestive system of a pig (Wenk, 2001). Dietary fiber can be further classified as soluble or insoluble fiber by their solubility character (Montagne et al., 2003). The main concern with soluble NSP in post-weaning diets is an increase in intestinal viscosity (Hopwood et al., 2006), as the passage rate of digesta is decreased, subsequently increasing the time digesta remains in the intestinal tract which can increase the colonization of harmful microorganisms (Kim et al., 2012). The differences between soluble and insoluble fiber may be due to their varying physicochemical properties (Molist et al., 2014). Insoluble fiber is resistant to fermentation and, consequently, less volatile fatty acids are produced. Insoluble fiber increases fecal bulkiness and passage rate, preventing colonization and proliferation of harmful bacteria (Jha and Berrocoso, 2015). The use of insoluble fiber is preferred in nursery diets post-weaning to decrease the instance of PWD, where soluble fiber can potentially increase the cases of enteric health challenges if fed directly after weaning.

In our study, diets were formulated to the same insoluble fiber content present in 4% coarse wheat bran; therefore, the oat hull diets were formulated to 1.85%, and the cellulose diets formulated to 1.55%. The inclusion of 4% coarse wheat bran was selected from previous research (Batson, unpublished data) based on work by Molist et al. (2010, 2011) concluding that 4% coarse wheat bran had no negative impacts on nursery pig performance, decreased the occurrence of gastrointestinal upsets in *E. coli* challenged pigs thus reducing PWD. Cellulose

acts as a hydrophilic bulking agent for feces and is predominately an insoluble fiber source (Chen et al., 2020). Molist et al. (2010) suggested that coarsely ground wheat bran blocks the adhesion of *E. coli* to intestinal epithelium, while oat hulls reduces the incidence of diarrhea in weaned pigs compared to pigs fed diets without oat hulls (Mateos et al., 2006). Jha and Berrocoso (2015) categorized wheat bran and oat hulls as being predominately insoluble fiber.

High levels of fiber in post-weaning diets have been thought to result in decreased digestibility and feed intake (Eggum, 1995) as fiber source, type, degree of lignification, and inclusion level account for the disparity in observed responses (Agyekum and Nyachoti, 2017). Mateos et al. (2006) recommended that 6 to 12 kg pigs be fed 6% NDF; however, Pascoal et al. (2012) fed diets containing 11% NDF without reducing piglet performance. In the present study, fiber inclusion and the source of fiber providing insoluble NSP did not impact any growth criteria throughout the 45-d trial. Molist et al. (2010) supports these findings as the inclusion of 4% wheat bran did not elicit any improvements or negative effects on the growth of *E. coli* challenged pigs. Pascoal et al. (2012) also observed no evidence for differences in pig performance when diets were balanced for crude fiber, thus diets contained 1.5% purified cellulose, 3% soybean hulls, or 9% citrus pulp. In the current study, insoluble fiber ranged from 6.4 to 5.8% in phase 1 and 8.5 to 8.0% in phase 2, respectively. The insoluble fiber content was much lower in the present study compared to Pascoal et al. (2012), as the insoluble fiber content in experimental diets ranged from 22.7 to 18.1%. Kim et al. (2008) fed 2% oat hulls to rice or wheat based post-weaning diets to non-challenged pigs and concluded that oat hull supplementation did not impact performance, whereas the insoluble fiber content ranged from 2.0% in the rice diet to 8.3% in the wheat diet. Contrasting to our results, Gerritsen et al. (2012) fed pigs 15% insoluble fiber in the form of 5% wheat straw and 10% oat hulls resulting in

increased feed intake and feed efficiency compared to pigs fed a highly digestible protein and standard cereal diet. A study conducted by Chen et al. (2020) fed 1% lignocellulose and 1% inulin as an insoluble and soluble fiber source respectively, alone and in combination immediately after weaning and only during the last two weeks of the nursery phase. The authors concluded insoluble fiber was more beneficial if fed directly after weaning due to improvements in growth performance. Interestingly, performance for pigs fed a combination of both fiber types increased in late nursery thought to be due to enhanced nutrient digestibility and microbial function (Chen et al., 2020). It appears further research is needed to determine the level of insoluble fiber to elicit consistent performance responses.

While fiber source did not affect growth performance, it is possible that the insoluble fiber source or fiber inclusion level affected fecal dry matter percentage during the experimental phase (d 0 to 24), as pigs fed diets with cellulose had increased fecal dry matter compared to pigs fed no fiber. According to Jha and Berrocoso (2015), coarse wheat bran has been suggested to contain 7.2% cellulose and oat hulls to contain 8.2% cellulose. Therefore, the increase in fecal dry matter in the present study could be attributed to a cellulose response rather than insoluble fiber, as pigs fed the cellulose diets had much higher cellulose levels compared to the coarse wheat bran and oat hull diets. Chen et al. (2020) observed reductions in the rate of diarrhea in the first two weeks post-weaning for pigs fed 1% lignocellulose while *Lactobacillus*, a strain of beneficial bacteria, was increased in the ileum of pigs fed the insoluble fiber source. Similar results were reported by Pascoal et al. (2012) as 1.5% purified cellulose fed to pigs modified intestinal microbiota therefore minimizing incidences of diarrhea. A higher occurrence of diarrhea for pigs fed diets with 3% soybean hulls and 9% citrus pulp was observed compared to

pigs fed diets with purified cellulose as soybean hulls and citrus pulp contain higher levels of soluble fiber.

There is evidence that diets formulated with low CP and cereal grains other than corn can improve nursery pig intestinal health (Stein and Kil, 2006). In the present study, no CP level × insoluble fiber source interactions were observed for any growth criteria or fecal dry matter percentage. Hermes et al. (2009) fed a high and low CP diet (20 or 16% CP) with high or low dietary fiber (7.2 or 5.3% NDF) with the supplementation of 4% wheat bran and 2% sugar beet pulp to the high fiber diet. The authors observed no dietary fiber × CP level interactions on growth performance; however, supplementing high dietary fiber to the low CP diet resulted in increased antibiotic treatments and decreased fecal score, therefore meaning looser feces. Hermes et al. (2009) may have increased gastrointestinal upsets by feeding fiber diets containing soluble fiber, as Kim et al. (2008) concluded the development of clinical PWD depended on the ratio of soluble, fermentable fiber to fermentable protein in the gastrointestinal tract. Bikker et al. (2006) conducted a factorial experiment with 22 or 15% CP level with high (13.4%) or low (7.5%) levels of fermentable carbohydrates with the addition of 8.43% wheat middlings and 4% sugar beet pulp to the high fiber diet. These authors did not observe any interactions for bacterial counts or morphological functional characteristics of the small intestine between dietary fiber and fermentable protein level. Jearound et al. (2008) conducted a factorial experiment evaluating 10% poultry meal as a fermentable protein source, 5% beet pulp as a fermentable fiber source, and a combination of the fermentable protein and fiber sources. No interactive effects were observed for growth performance, microbial populations, or fermentation products similar to results observed by Bikker et al. (2006).

In conclusion, reducing crude protein decreased growth performance while minimal improvements in fecal dry matter was observed during the treatment period. The source or inclusion of insoluble fiber in nursery diets had no impact on performance; however, the inclusion of cellulose in nursery diets improved fecal dry matter compared to feeding no dietary fiber or wheat bran.

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Table 2-1 Analyzed chemical fiber composition of ingredients[1]

	Fiber source		
Analyzed composition, %	Wheat bran	Oat hulls	Cellulose[3]
ADF	12.8	45.2	65.9
NDF	42.4	81.0	78.0
Total dietary fiber	44.7	85.3	96.0
Insoluble fiber[2]	41.6	83.6	93.9
Soluble fiber	3.1	1.7	2.1

[1]Analyzed by University of Illinois (Urbana – Champaign, IL)

[2]Treatment diets were formulated to balance for analyzed insoluble fiber content.

[3]Arbocel (J. Rettenmaier USA, Schoolcraft, MI).

Table 2-2 Phase 1 diet composition (as-fed basis)[1]

	Fiber source and crude protein:							
	No fiber		Wheat bran		Oat hulls		Cellulose	
	21%	18%	21%	18%	21%	18%	21%	18%
Ingredient, %								
Corn	44.85	52.30	41.50	49.00	42.95	50.40	43.00	50.45
Soybean meal, 46.5% CP	18.10	10.40	17.45	9.75	18.20	10.50	18.35	10.65
Coarse wheat bran	---	---	4.00	4.00	---	---	---	---
Oat hulls	---	---	---	---	1.85	1.85	---	---
Cellulose[2]	---	---	---	---	---	---	1.55	1.55
Fishmeal	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50
Dried whey	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00
Enzymatically treated soybean meal[3]	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75
Soybean oil	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Calcium carbonate	0.30	0.35	0.35	0.40	0.23	0.25	0.30	0.35
Monocalcium phosphate, 21%	0.20	0.30	0.10	0.20	0.20	0.30	0.20	0.30
Salt	0.30	0.33	0.30	0.33	0.30	0.33	0.30	0.33
L-Lysine	0.43	0.48	0.44	0.49	0.43	0.48	0.42	0.47
DL-Methionine	0.22	0.20	0.22	0.20	0.22	0.20	0.22	0.20
L-Threonine	0.20	0.21	0.20	0.21	0.20	0.21	0.20	0.21
L-Tryptophan	0.07	0.08	0.07	0.08	0.07	0.08	0.07	0.08
L-Valine	0.14	0.17	0.14	0.17	0.14	0.17	0.14	0.17
Trace mineral premix[4]	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Vitamin premix[5]	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Phytase[6]	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Total	100	100	100	100	100	100	100	100
Calculated analysis								
Standardized digestible (SID) amino acids, %								
Lysine	1.40	1.25	1.40	1.25	1.40	1.25	1.40	1.25
Isoleucine:lysine	56	53	56	52	56	52	56	53
Leucine:lysine	110	108	108	106	109	107	109	108
Methionine:lysine	37	38	37	38	37	38	37	38

Methionine and cysteine:lysine	57	57	58	58	57	57	57	57
Threonine:lysine	64	64	64	64	64	64	64	64
Tryptophan:lysine	21.0	20.9	21.1	21.0	21.0	20.9	21.1	21.0
Valine:lysine	70	70	70	70	70	70	70	70
Total lysine, %	1.54	1.37	1.54	1.37	1.58	1.41	1.54	1.37
Metabolizable energy, kcal/kg	3,436	3,439	3,395	3,399	3,401	3,406	3,384	3,386
Net energy, kcal/kg	2,589	2,631	2,554	2,596	2,559	2,600	2,548	2,587
SID lysine:NE, g/Mcal	5.40	4.74	5.47	4.81	5.46	4.80	5.49	4.82
Crude protein, %	21.0	18.0	21.0	18.0	21.0	18.0	21.0	18.0
Calcium, %	0.65	0.66	0.65	0.66	0.65	0.66	0.65	0.66
Phosphorus, %	0.62	0.61	0.63	0.61	0.65	0.64	0.62	0.61
STTD P, %[7]	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
Insoluble fiber, %	5.0	4.4	6.4	5.8	6.4	5.8	6.4	5.8
Insoluble:soluble fiber	4.5	5.1	5.4	6.2	5.7	6.6	5.6	6.5

[1]Phase 1 diets were fed from approximately 5.0 to 5.6 kg.

[2]Arbocel (J. Rettenmaier USA, Schoolcraft, MI)

[3]HP 300 (Hamlet Protein, Findlay, OH).

[4]Provided per kg of premix: 73 g Zn from Zn sulfate; 73 g Fe from iron sulfate; 22 g Mn from manganese oxide; 11 g Cu from copper sulfate; 0.2 g I from calcium iodate; 0.2 g Se from sodium selenite.

[5]Provided per kg of premix: 3,527,399 IU vitamin A; 881,850 IU vitamin D; 17,637 IU vitamin E; 1,764 mg vitamin K; 15.4 mg vitamin B12; 33,069 mg niacin; 11,023 mg pantothenic acid; 3,307 mg riboflavin.

[6]Ronozyme HiPhos 2700 (DSM Nutritional Products, Parsippany, NJ) provided an estimated release of 0.10% STTD P.

[7]Standardized total tract digestible phosphorus.

Table 2-3 Phase 2 diet composition (as-fed basis)[1]

	Fiber source and crude protein:							
	No fiber		Wheat bran		Oat hulls		Cellulose	
	21%	18%	21%	18%	21%	18%	21%	18%
Ingredient, %								
Corn	56.10	63.80	52.80	60.45	54.20	61.90	54.15	61.95
Soybean meal, 46.5% CP	30.00	22.00	29.35	21.30	30.15	22.05	30.45	22.20
Coarse wheat bran	---	---	4.00	4.00	---	---	---	---
Oat hulls	---	---	---	---	1.85	1.85	---	---
Cellulose[2]	---	---	---	---	---	---	1.55	1.55
Dried whey	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
Calcium carbonate	0.98	0.98	1.03	1.03	0.90	0.88	0.98	0.98
Monocalcium phosphate, 21%	0.80	0.90	0.70	0.80	0.80	0.90	0.80	0.90
Salt	0.55	0.58	0.55	0.58	0.55	0.58	0.55	0.58
L-Lysine	0.47	0.60	0.48	0.61	0.47	0.60	0.46	0.59
DL-Methionine	0.21	0.23	0.21	0.23	0.21	0.23	0.21	0.23
L-Threonine	0.21	0.26	0.21	0.26	0.21	0.26	0.21	0.26
L-Tryptophan	0.06	0.08	0.06	0.08	0.06	0.08	0.06	0.08
L-Valine	0.13	0.20	0.13	0.20	0.13	0.20	0.13	0.20
L-Isoleucine	---	0.03	---	0.03	---	0.03	---	0.03
Trace mineral premix[3]	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Vitamin premix[4]	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Phytase[5]	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Total	100	100	100	100	100	100	100	100
Calculated analysis								
Standardized digestible (SID) amino acids, %								
Lysine	1.35	1.25	1.35	1.25	1.35	1.25	1.35	1.25
Isoleucine:lysine	56	52	56	52	56	52	57	52
Leucine:lysine	114	107	112	105	113	106	113	107
Methionine:lysine	36	37	36	37	36	37	36	37
Methionine and cysteine:lysine	57	57	58	58	57	57	57	57
Threonine:lysine	64	64	64	64	64	64	64	64

Tryptophan:lysine	20.8	20.9	20.9	21.0	20.8	20.9	20.9	20.9
Valine:lysine	70	70	70	70	70	70	70	70
Total lysine, %	1.49	1.37	1.49	1.37	1.53	1.41	1.49	1.37
Metabolizable energy, kcal/kg	3,278	3,287	3,238	3,247	3,245	3,254	3,225	3,234
Net energy, kcal/kg	2,431	2,477	2,394	2,442	2,398	2,446	2,387	2,433
SID lysine:NE, g/Mcal	5.54	5.04	5.63	5.11	5.62	5.10	5.65	5.12
Crude protein, %	21.0	18.0	21.0	18.0	21.0	18.0	21.0	18.0
Calcium, %	0.76	0.75	0.76	0.75	0.76	0.75	0.76	0.75
Phosphorus, %	0.60	0.58	0.61	0.59	0.63	0.61	0.60	0.58
STTD P, %[6]	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49
Insoluble fiber, %	7.1	6.6	8.5	8.0	8.6	8.0	8.5	8.0
Insolbule:soluble fiber	4.3	4.6	4.9	5.3	5.1	5.5	5.0	5.5

[1]Phase 2 diets were fed from approximately 5.6 to 10.0 kg.

[2]Arbocel (J. Rettenmaier USA, Schoolcraft, MI)

[3]Provided per kg of premix: 73 g Zn from Zn sulfate; 73 g Fe from iron sulfate; 22 g Mn from manganese oxide; 11 g Cu from copper sulfate; 0.2 g I from calcium iodate; 0.2 g Se from sodium selenite.

[4]Provided per kg of premix: 3,527,399 IU vitamin A; 881,850 IU vitamin D; 17,637 IU vitamin E; 1,764 mg vitamin K; 15.4 mg vitamin B12; 33,069 mg niacin; 11,023 mg pantothenic acid; 3,307 mg riboflavin.

[5]HiPhos 2700 (DSM Nutritional Products, Parsippany, NJ) provided an estimated release of 0.10% STTD P.

[6]Standardized total tract digestible phosphorus.

Table 2-4 Phase 3 common diet composition, (as-fed basis)[1]

Ingredient	%
Corn	65.47
Soybean meal, 46.5% CP	28.30
Choice white grease	2.00
Calcium carbonate	0.75
Monocalcium phosphate, 21% P	1.10
Sodium chloride	0.60
L-Lysine-HCl	0.55
DL-Methionine	0.25
L-Threonine	0.23
L-Tryptophan	0.05
L-Valine	0.16
Trace mineral premix[2]	0.15
Vitamin premix with phytase[3]	0.25
Pellet stabilizer[4]	0.15
Total	100.00
SID amino acids, %	
Lysine	1.30
Isoleucine:lysine	53
Leucine:lysine	111
Methionine:lysine	39
Met and cysteine:lysine	60
Threonine:lysine	63
Tryptophan:lysine	19.3
Valine:lysine	70
Histidine:lysine	35
Total Lysine, %	1.41
Metabolizable energy, kcal/kg	3,318
Net energy, kcal/kg	2,534
Crude protein, %	19.9
Calcium, %	0.65
STTD P[5], %	0.48
Insoluble fiber, %	7.5
Insoluble fiber:soluble fiber	4.4

[1]Phase 3 common diet was fed from d 24 to 45.

[2]Provided per kg of premix: 73 g Zn from Zn sulfate; 73 g Fe from iron sulfate; 22 g Mn from manganese oxide; 11 g Cu from copper sulfate; 0.2 g I from calcium iodate; 0.2 g Se from sodium selenite.

[3]Ronozyme HiPhos GT 2700 (DSM Nutritional Products, Parsippany, NJ) provided an expected P release of 0.10%. Provided per kg of premix: 3,527,399 IU vitamin A; 881,850 IU vitamin D; 17,637 IU vitamin E; 1,764 mg vitamin K; 15.4 mg vitamin B12; 33,069 mg niacin; 11,023 mg pantothenic acid; 3,307 mg riboflavin.

[4]Alltech All-Bind HD (Alltech, Nicholasville, KY).

[5]STTD P = standardized total tract digestible phosphorus.

Table 2-5 Analyzed diet composition (as-fed basis)[1]

	Fiber source and crude protein:							
	No fiber		Wheat bran		Oat hulls		Cellulose[3]	
Analyzed composition, %	21%	18%	21%	18%	21%	18%	21%	18%
Phase 1								
Dry matter	90.82	89.95	90.24	90.28	91.43	91.08	90.93	90.76
Crude fiber	3.20	3.05	2.90	2.90	2.80	2.80	3.75	4.15
Acid detergent fiber	2.50	2.35	2.85	3.30	3.30	3.15	4.05	3.25
Neutral detergent fiber	5.75	6.10	7.75	7.30	7.10	7.65	9.20	8.30
Crude protein	19.80	17.25	20.25	17.15	20.55	17.30	20.15	17.25
Phase 2								
Dry matter	89.17	88.99	88.74	89.17	89.11	88.93	89.17	89.43
Crude fiber	2.60	2.65	3.85	2.80	2.75	2.70	4.0	3.75
Acid detergent fiber	3.05	2.45	3.45	3.10	3.40	3.10	4.25	4.30
Neutral detergent fiber	7.40	6.50	8.05	7.30	6.75	6.45	7.80	8.65
Crude protein	19.70	17.05	20.30	17.05	19.85	17.05	19.60	16.90

[1]Diets were fed in 2 phases from d 0 to 10 and d 10 to 24, for phases 1 and 2, respectively.

[2]Complete diet samples were taken at feed manufacturing. Samples were stored at -20°C until they were homogenized and subsampled. Duplicate samples per treatment were submitted to Ward Laboratories, Inc., Kearney, NE for proximate analysis.

[3]Arbocel (J. Rettenmaier USA, Schoolcraft, MI).

Table 2-6 Interactive effects of fiber source and crude protein (CP) on nursery pig performance[1]

	Fiber source and crude protein[2]:									
	None		Wheat bran		Oat hulls		Cellulose[3]			Probability, *P*
Item	21%	18%	21%	18%	21%	18%	21%	18%	SEM	Fiber × CP
BW, kg										
d 0	5.0	4.9	5.0	4.9	5.0	5.0	5.0	5.0	0.05	0.376
d 10	5.8	5.5	5.7	5.4	5.8	5.5	5.7	5.6	0.08	0.752
d 24	10.3	9.7	10.2	9.6	10.2	9.8	10.2	9.7	0.28	0.881
d 45	22.3	21.0	21.4	20.7	22.0	21.6	21.9	21.3	0.55	0.783
d 0 to 10										
ADG, g	75	57	67	51	78	52	73	64	9.2	0.701
ADFI, g	108	106	102	93	111	98	103	108	11.4	0.414
G:F, g/kg	687	533	628	530	691	502	705	583	44.4	0.753
d 10 to 24										
ADG, g	327	302	324	293	316	307	319	292	17.4	0.849
ADFI, g	409	400	418	387	397	401	421	388	23.0	0.604
G:F, g/kg	801	754	777	759	796	766	760	753	15.8	0.618
d 0 to 24 (Experimental period)										
ADG, g	222	200	216	192	217	199	217	197	12.9	0.989
ADFI, g	283	277	285	264	278	273	288	271	17.6	0.853
G:F, g/kg	784	720	756	727	781	729	752	724	14.1	0.499
d 24 to 45 (Common diet)										
ADG, g	569	537	531	531	560	561	556	552	15.5	0.639
ADFI, g	790	751	746	731	764	767	779	755	29.3	0.702
G:F, g/kg	722	718	715	727	734	732	713	733	15.9	0.510
d 0 to 45										
ADG, g	384	357	362	349	377	367	374	363	13.1	0.840
ADFI, g	520	498	498	480	505	502	515	497	23.0	0.896

G:F, g/kg	740	719	728	727	748	731	726	730	12.7	0.243

[1]A total of 360 pigs (Line 200 × 400, DNA, Columbus, NE, initial BW of 5.0 ± 0.1 kg) were used in a 45-d growth study with 5 pigs per pen and 9 pens per treatment.

[2]Analyzed insoluble fiber values for coarse wheat bran, oat hulls, and cellulose were used in diet formulation to provide a similar amount of insoluble fiber in all diets that contained a fiber source by balancing the insoluble fiber content provided by 4% coarse wheat bran.

[3]Arbocel (J. Rettenmaier USA, Schoolcraft, MI).

Table 2-7 Main effects of fiber source and crude protein (CP) on nursery pig performance[1]

	CP				Fiber source[2]					
Item	21%	18%	SEM	*P*-value	None	Wheat bran	Oat hulls	Cellulose[3]	SEM	*P*-value
BW, kg										
d 0	5.0	5.0	0.05	0.193	5.0	5.0	5.0	5.0	0.05	0.816
d 10	5.7	5.5	0.04	< 0.001	5.7	5.7	5.6	5.6	0.06	0.485
d 24	10.2	9.7	0.20	0.002	10.0	9.9	9.9	10.0	0.23	0.934
d 45	21.9	21.2	0.37	0.038	21.8	21.6	21.1	21.7	0.44	0.438
d 0 to 10										
ADG, g	73	56	6.7	0.001	65	68	59	66	7.6	0.580
ADFI, g	106	101	10.3	0.218	104	106	98	107	10.7	0.405
G:F, g/kg	678	537	22.4	< 0.001	597	643	579	610	31.5	0.521
d 10 to 24										
ADG, g	321	298	12.7	0.020	312	305	309	314	14.4	0.919
ADFI, g	411	394	18.5	0.128	399	404	402	404	20.1	0.985
G:F, g/kg	784	758	8.0	0.023	781	756	768	777	11.2	0.419
d 0 to 24 (Experimental period)										
ADG, g	218	197	10.0	0.003	208	207	204	211	11.0	0.903
ADFI, g	284	271	14.9	0.111	275	280	275	280	15.8	0.926
G:F, g/kg	768	725	7.1	< 0.001	755	738	742	752	10.0	0.562
d 24 to 45 (Common diet)										
ADG, g	554	546	8.7	0.416	561	554	531	553	11.5	0.226
ADFI, g	769	751	24.7	0.160	766	767	738	770	26.3	0.283
G:F, g/kg	721	728	13.7	0.330	733	723	721	720	14.5	0.469
d 0 to 45										
ADG, g	374	359	9.4	0.048	372	368	355	371	10.8	0.366
ADFI, g	509	495	19.9	0.121	504	506	489	509	21.0	0.464

G:F, g/kg	735	727	11.0	0.116	740	728	728	729	11.6	0.306

[1]A total of 360 pigs (Line 200 × 400, DNA, Columbus, NE, initial BW of 5.0 ± 0.1 kg) were used in a 45-d growth study.

[2]Analyzed insoluble fiber values for coarse wheat bran, oat hulls, and cellulose were used in diet formulation to provide a similar amount of insoluble fiber in all diets that contained a fiber source by balancing the insoluble fiber content provided by 4% coarse wheat bran.

[3]Arbocel (J. Rettenmaier USA, Schoolcraft, MI).

Table 2-8 Interactive effects of fiber source and crude protein (CP) in nursery pig diets on fecal dry matter, %[1]

	Fiber source and crude protein:[2]									
Day of	None		Wheat bran		Oat hulls		Cellulose[3]			Probability, *P*
Collection	21%	18%	21%	18%	21%	18%	21%	18%	SEM	Fiber × CP
d 10	23.8	26.2	25.6	25.6	27.0	28.1	29.3	28.7	1.13	0.409
d 17	19.3	22.4	22.0	23.2	22.5	23.9	20.8	26.1	0.93	0.128
d 24[4]	22.0	22.2	20.6	22.6	22.2	23.2	24.3	25.1	0.80	0.819
d 45	27.0	27.0	27.7	25.8	25.3	26.8	25.4	25.3	0.92	0.376

[1]Values represent the mean of 3 pigs per pen and 9 pens per treatment. Three pigs per pen were randomly selected and sampled. Fecal samples were then pooled by pen respective of day of collection and dried at 55°C for 48-h in a forced air oven.

[2]Diets containing a fiber source were formulated on the insoluble fiber content of the respective ingredient.

[3]Arbocel (J. Rettenmaier USA, Schoolcraft, MI).

[4]Experimental diets were fed from d 0 to 24 and a common diet was fed from d 24 to 45.

Table 2-9 Main effects of fiber source and crude protein (CP) in nursery pig diets on fecal dry matter, %[1]

	CP				Fiber source[2]					
Day of Collection	21%	18%	SEM	*P*-value	None	Wheat bran	Oat hulls	Cellulose[3]	SEM	*P*-value
d 10	26.4	27.2	0.56	0.279	25.0[b]	25.6[b]	27.6[ab]	29.0[a]	0.80	< 0.001
d 17	21.1	23.9	0.46	< 0.001	20.9[b]	22.6[ab]	23.2[ab]	23.5[a]	0.66	0.028
d 24[4]	22.3	23.3	0.40	0.143	22.1[b]	21.6[b]	22.7[ab]	24.7[a]	0.57	0.006
d 45	26.4	26.2	0.46	0.831	27.0	26.8	26.0	25.3	0.65	0.296

[ab]Means in the same row with different superscripts differ ($P < 0.05$).

[1]Values represent the mean of 3 pigs per pen. Three pigs per pen were randomly selected and sampled. Fecal samples were then pooled by pen respective of day of collection and dried at 55°C in a forced air oven.

[2] Diets containing a fiber source were formulated on the insoluble fiber content of the respective ingredient.

[3]Arbocel (J. Rettenmaier USA, Schoolcraft, MI).

[4]Experimental diets were fed from d 0 to 24 and a common diet was fed from d 24 to 45.

Chapter 3 - Effect of high phytase supplementation in lactation diets on sow and litter performance

Abstract

A total of 109 sows (Line 241; DNA, Columbus, NE) were used to evaluate the effect of increasing dietary phytase in lactation diets on sow and litter performance. On d 107 of gestation, sows were blocked by body weight and parity and allotted to 1 of 3 dietary treatments of increasing phytase concentration (0, 1,000, or 3,000 FYT/kg; Ronozyme Hi Phos GT 2700, DSM Nutritional Products, Inc., Parsippany, NJ). The control diet contained no phytase and was formulated to contain 0.50% standardized total tract digestible phosphorus (STTD P; 0.45% available P) and 0.62% STTD Calcium (0.90% total Ca). The phytase diets that contained 1,000 or 3,000 FYT/kg were also formulated to 0.50% STTD P and 0.62% STTD Ca including the release of 0.132% STTD P and 0.096% STTD Ca. Diets were balanced for net energy and fed from d 107 of gestation until weaning (d 18 ± 3). All farrowings were monitored, with farrowing duration starting at the time the first pig was born until the first dispersal of placental tissues with no subsequent pigs born. Litters were cross-fostered within treatment until 48 h post-farrowing to equalize litter size. There were no differences among treatments in sow body weight at d 107 of gestation, 24-h after farrowing, or at weaning. Sow average daily feed intake from farrowing to weaning tended to increase (linear, $P = 0.093$) as phytase increased. There was no evidence for difference in the number of total born pigs, as well as the percentage of stillborns, mummies, and born alive pigs at the completion of farrowing. Similarly, phytase supplementation did not influence ($P > 0.05$) wean-to-estrus interval, lactation length, or litter size after cross-fostering among dietary treatments. Although not significant (linear, $P = 0.226$), farrowing duration

decreased as added phytase increased with a decrease of 47 minutes (12%) for 3,000 FYT compared to the control. There were no differences in pig weight at weaning, but as a result of increased survivability (linear, $P = 0.002$), litter weaning weight and overall litter weight gain increased (quadratic, $P < 0.05$) up to 1,000 FYT of added phytase with no further benefit observed in sows fed 3,000 FYT. In conclusion, sow feed intake tended to increase linearly with increasing added phytase. Feeding 1,000 FYT/kg maximized overall litter gain and weaning weight; however, a larger scale study with more sows is needed to determine the optimal addition of phytase in lactation diets to reduce farrowing duration.

Key Words: farrowing duration, lactation, phosphorus, phytase, sow

Introduction

Phosphorus is an essential nutrient necessary for skeletal mineralization, growth, and many other physiological processes in pigs (Kebreab et al., 2012). Phytate (*myo*-inositol hexakisdihydrogen phosphate; IP_6), a structure with six phosphate molecules surrounding a *myo*-inositol ring, accounts for 60 to 80% of the total phosphorus (P) storage in grains, legumes, and oilseeds (Selle and Ravindran, 2008). The requisite enzyme needed to degrade phytate-P is available through endogenous phytase produced by the mucosa of the small intestine, gut microflora phytase activity present in the large intestine, intrinsic plant phytase activity, and the inclusion of dietary exogenous phytase (Humer et al., 2015). Monogastrics are unable to completely utilize phytate-P due to poor substrate solubility in the small intestine rather than low endogenous phytase activity, leading to increased need for dietary P supplementation and excretion of phosphorus to the environment (Adeola and Cowieson, 2011).

The inclusion of high concentrations of microbial phytase in P adequate diets to improve nursery pig growth performance has been documented (Beers and Jongbloed, 1992; Gourley et al., 2018; Holloway et al., 2019). High levels of exogenous phytase are suggested to decrease anti-nutritional effects associated with IP_6 (phytate) through extra-phosphoric pathways by increasing the digestibility of energy, amino acids, and minerals. The exact mechanisms for improvements in performance experienced from high levels of dietary phytase are unknown; however, perhaps lactating sows may benefit from feeding high concentrations of phytase such as found for nursery pigs. Parturition is a process that requires a high level of metabolic energy, as modern sow genotypes experience extended farrowing durations with increased litter size (Tokach et al., 2019). This combination can result in an increased stillborn rate (van Dijk et al., 2005). Sows are required to nurse large litters and commonly meet the demand for nutrients by mobilizing body reserves (Pedersen et al. 2019).

The inclusion of microbial phytase has been shown to increase P digestibility in sow diets (Kemme et al., 1997; Badioo et al., 2003) while P excretion was decreased in sows fed a corn-soybean-meal diet supplemented with 500 FYT/kg (Torrallardona et al., 2012). Sows also fed a low-P diet supplemented with 500 FYT/kg of phytase experienced similar performance to that of sows fed a positive control diet (Nasir et al., 2014). Data regarding phytase dose response effects on lactating sow performance is scarce (Jongbloed et al., 2004). Welleans et al. (2015) observed decreased BW loss for sows fed a low-P diet supplemented with 2,000 FTU/kg of phytase. Manu et al. (2018) observed that feeding 2,500 FTU/kg of phytase in lactation diets formulated to adequate P levels had no effect on sow performance; however, a reduction in farrowing duration and the number of stillborn pigs was observed. These results are interesting to consider for the modern, high producing sow, but there is no data available to confirm this response. Therefore,

the objective of this study was to determine the effect of increasing amounts of phytase fed to lactating sows on farrowing duration and sow and litter performance.

Materials and Methods

The Kansas State University Institutional Animal Care and Use Committee approved the protocol for this study. The study was conducted at the Kansas State University Swine Teaching and Research Center in Manhattan, KS. A total of 109 sows (Line 241; DNA, Columbus, NE) were used across four consecutive batch farrowing groups from November 2018 to March 2019. On approximately d 107 of gestation, sows were weighed and moved into the farrowing house. Females were blocked by initial body weight and parity, then allotted to 1 of 3 dietary treatments within those blocks.

Dietary treatments were corn-soybean meal-based and consisted of increasing concentration of phytase (0, 1,000, or 3,000 FYT/kg). The control diet containing no phytase was formulated to 0.50% standardized total tract digestible phosphorus (STTD P; 0.45% available P) and 0.62% STTD calcium (0.90% total Ca; Table 3-1). Coefficients for STTD P were obtained from NRC (2012), and values for STTD Ca were obtained from Stein et al. (2016). Contributions of Ca from vitamin and trace mineral premixes were accounted for in diet formulation. Both phytase diets were also formulated to 0.50% STTD P and 0.62% STTD Ca including the release of 0.132% STTD P and 0.096% STTD Ca by phytase as recommended by the manufacturer (DSM Nutritional Products, Inc., Parsippany, NJ). The same release values were used for both phytase diets. The commercially available phytase used in this study is a coated fungal phytase from *Citrobacter braakii* expressed in *aspergillus oryzae* (Ronozyme Hi Phos GT 2700, DSM Nutritional Products, Inc., Parsippany, NJ). Diets were balanced for net energy (NE) by altering

amounts of choice white grease. All other nutrients met or exceeded the NRC (2012) requirement estimates.

From d 107 of gestation until farrowing (approximately d 116), sows were offered up to 2.7 kg/d of their respective treatment diets. Postpartum, sows were allowed ad libitum access to feed distributed by an electronic feeding system (Gestal Solo Feeders Jyga Technologies, Quebec City, Quebec, Canada). Sow feed intake was recorded by weighing the amount of feed placed in a feed hopper and the amount remaining every 7 d until weaning (d 18 ± 3).

Farrowing duration was monitored by 24-hour care where the initiation of farrowing was classified as the birth of the first piglet and the completion of farrowing was determined by the first dispersal of placental tissues with no subsequent pigs born. From the onset of farrowing, sows were checked in 15-minute intervals and were sleeved if the time between births reached 30 to 45 minutes. Oxytocin (Bimeda, Inc., Oakbrook Terrace, IL) was administered in 1 or 2 cc doses to gilts and sows, respectively, who produced no piglets when sleeved and the time in between births was greater than approximately 2 hours. Sows were excluded from the study if retained fetuses were expelled 24 hours after a sow's parturition time was recorded or if initial farrowing time could not be determined. Farrowing duration data were collected on 101 of the 109 sows enrolled in the study. Sow body weight was measured 24 h after farrowing and at weaning. Cross fostering occurred within dietary treatment until 48 h postpartum in an attempt to equalize litter size (minimum of 10 pigs per litter). Litters were weighed on d 2, 7, and 14 post-farrowing, and at weaning. Piglet survivability was calculated as the number of pigs weaned per sow divided by the number of pigs on d 2 after cross fostering was completed.

At weaning (average of 18.2 d post farrowing and range of 15- to 21-d), sows were moved to a breeding barn, individually housed, and checked daily for signs of estrus using a

boar. The wean-to estrus interval (WEI) was determined as the number of days between weaning and when sows were first observed to show a positive response to the back-pressure test.

Diets were manufactured at the Kansas State University O.H. Kruse Feed Technology Innovation Center in Manhattan, KS. A new batch of each treatment diet was manufactured for each farrowing group and packaged in 22 kg bags. During bagging, feed samples were collected from every fifth bag, pooled, and stored at -20°C and later homogenized for nutrient analysis.

Four samples (one per batch) per dietary treatment from the pooled feed samples were sent to a commercial laboratory (Ward Laboratories, Kearney, NE) for CP (AOAC 990.03, 2006), Ca (method 6.3; Kovar, 2003), and P analysis (method 6.3; Kovar, 2003). In addition, 4 samples (one per batch) per dietary treatment were sent to another laboratory (DSM Nutritional Products, Inc., Belvidere, NJ) for phytase analysis (Table 3-2).

Statistical analysis

Data were analyzed using the lmer function from the lme4 package in R (version 3.5.1 (2018-07-12)) where sow was the experimental unit, dietary treatment was a fixed effect, and sow group and block were random effects. Statistical models were fit using RStudio (Version 3.5.2, R Core Team. Vienna, Austria). Pre-planned linear and quadratic contrast statements were used to evaluate increasing phytase concentration. Pre-determined polynomial orthogonal contrasts were used to account for unequal spacing in phytase doses.

Sow ADFI, BW, litter weight, litter gain, piglet gain, and lactation length were analyzed assuming a normal distribution of the response variable. Litter weight on d 2 was used as a covariate for d 7, 14, and weaning litter weights and litter weight gain to improve the fit of the model. Pig weight on d 2 was used as a covariate for d 7, 14, and weaning pig weights to

improve the fit of the model. In these cases, residual assumptions were checked using standardized residuals and were found to be reasonably met.

Litter counts, wean-to-estrus interval, and the duration of farrowing were analyzed using a negative binomial distribution. Total born, born alive, stillborn, mummified fetuses, and piglet survivability were analyzed using a binomial distribution. All results were considered significant at $P \leq 0.05$, and marginally significant at $0.05 \leq P \leq 0.10$.

Results and Discussion

Chemical Analysis

Chemical analysis of DM, CP, Ca, and P of the experimental diets were similar to the formulated values (Table 3-2). Analyzed phytase concentration increased as phytase addition increased as anticipated.

Sow Performance

Phytase is commonly added to swine diets at 500 to 1,000 FTU/kg to release 0.10 to 0.15% available P (Wilcock and Walk, 2016) and higher concentrations of 1,500 FTU/kg or above are considered “super-dosing” levels. The main objective of this study was to determine if the extra-phosphoric effects of feeding “super-dose” levels of phytase to lactating sows with diets formulated to adequate P levels influences sow or litter performance.

The addition of microbial phytase to sow diets formulated to low levels of P has been well documented to improve P digestibility resulting in a reduction of fecal P excretion (Kemme et al., 1997; Nasir et al., 2014) while maintaining performance through lactation (Baidoo et al., 2003; Jongbloed et al., 2004). In our study, there were no differences observed among treatments in body weight at d 107 of gestation, 24-h after farrowing, or at weaning (Table 3-3). Regardless of dietary treatment, sows lost an average of 10.5 kg due to the inability of voluntary feed intake

to completely support nutrient demands during lactation. A previous study observed a decrease in bodyweight loss experienced by lactating sows when fed 2,000 FTU/kg of phytase in a diet with P levels below NRC (2012) requirement estimates (Wealleans et al., 2015). While no differences between treatments were observed in our study, this could be attributed to all treatment diets formulated to meet or exceed NRC (2012) requirement estimates.

Phytate has been suggested to be an appetite suppressant, thus feed intake may be increased by improving digestible nutrient intake with phytate degradation (Cowieson et al., 2011; Morales et al., 2016). From d 0 to 7 and 7 to 14 of lactation, ADFI was similar across treatments; however, from d 14 to weaning ADFI increased (linear, $P = 0.020$) with increasing dietary phytase and overall ADFI tended to increase (linear, $P = 0.093$) as phytase dosage increased. Average daily feed intake in the current study was 5.8 kg, similar to intake levels observed by Wealleans et al. (2015); however, in contrast, those authors observed no differences in sow feed intake regardless of phytase level. In addition, Manu et al. (2018) observed no influence of up to 2,500 FTU/kg added phytase on sow ADFI from d 109 of gestation to weaning. In some studies, "super-dose" levels of phytase fed to weanling pigs resulted in increased ADFI (Beers and Jongbloed, 1992; Kies et al., 2006), but in others, no differences were found (Holloway et al., 2019; Gourley et al., 2018), as these responses could be attributed to basal diets formulated at or below the P requirement. The mechanisms of "super dosing" phytase are still unknown, while the available literature is not clear on the effect of high levels of phytase on feed intake (Adeola and Cowieson, 2001). The efficacy of phytase is dependent on numerous factors including dietary Ca:P ratios, solubility of phytate in the gut, amount of added phytase, phytase source, and especially phytate substrate levels (Selle and Ravindran, 2008).

To evaluate increasing phytase level on farrowing duration, treatment diets were fed approximately one week before farrowing. There was no statistical difference (linear, $P = 0.226$) in farrowing duration; however, farrowing duration numerically decreased with increasing phytase dose similar to Manu et al. (2018). They observed a significant reduction in farrowing duration from 710.4 ± 83.63 to 521.5 ± 45.24 minutes monitoring 25 sows using infrared video cameras. In the present study, farrowing duration was generally much shorter averaging from 398 to 351 minutes, which could be attributed to differences in farrowing assistance protocols or litter size between studies. However, we still observed on average a 22 and 47-minute reduction in farrowing duration when 1,000 or 3,000 FYT/kg of phytase, respectively was fed.

Litter Performance

There was no evidence for difference in total born, percentage born alive, stillborn, or mummified pigs among dietary treatments (Table 3-4). Furthermore, the number of pigs at weaning and individual pig weight and weight gain were not affected by increasing added phytase. Interestingly, pig survivability increased (linear, $P = 0.002$) as added phytase increased. Although not significant, Manu et al. (2018) observed a numerical reduction of 1.7% units in pre-weaning mortality in sows fed 2,500 FTU/kg compared to the control sows fed diets with no added phytase. No evidence for differences were found for litter weight at d 2 or 7; however, litter weaning weight increased (quadratic, $P = 0.039$) and overall litter gain increased (quadratic, $P = 0.047$) with sows fed 1,000 FYT/kg having the heaviest litters. The NRC (2012) model for lactating sows was used to predict the cause of increased litter weaning weight, overall litter gain, and pig survivability for pigs born to sows fed diets supplemented with phytase. Sows fed high phytase levels had increased feed intake, as the NRC model estimated milk production increased from 9.3 to 9.8 and 9.9 kg/d with increasing concentration of phytase. Sow body

weight loss, projected whole body protein and lipid deposition across treatments were similar; therefore, we concluded that sows fed high levels of phytase were able to produce more milk per day which increased piglet survivability.

In conclusion, our results demonstrate that supplementing high levels of phytase in lactation diets linearly increased feed intake in lactating sows. Sows fed diets with 1,000 FYT/kg phytase had increased overall litter gain and weaning weight. The number of pigs surviving to weaning increased with increasing phytase up to 3,000 FYT/kg. Although not significant, farrowing duration numerically decreased for sows fed up to 3,000 FYT/kg which supports the need for additional research with more sows to determine the phytase impact on farrowing duration. This study presents interesting impacts on sow and litter performance due to high inclusions of dietary phytase; however, a commercial trial with more sows is warranted to determine the effects on farrowing duration.

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Table 3-1 Diet composition (as-fed basis)[1]

	Added phytase, FYT/kg	
Item	0	1,000/3,000
Ingredient, %		
Corn	63.30	64.40
Soybean meal, 46.5% CP	30.00	30.00
Choice white grease	2.40	2.00
Limestone	0.95	0.88
Monocalcium phosphate, 21%	1.78	1.10
Salt	0.50	0.50
L-Lysine-HCL	0.18	0.18
DL-Methionine	0.05	0.05
L-Threonine	0.10	0.10
L-Valine	0.12	0.12
Sow add pack[2]	0.25	0.25
Vitamin premix[3]	0.25	0.25
Trace mineral premix[4]	0.15	0.15
Phytase[5]	---	0.04 / 0.11
Total	100	100
Calculated analysis		
Standardized ileal digestible (SID) amino acids, %		
Lysine	1.05	1.05
Isoleucine:lysine	68	68
Leucine:lysine	141	142
Methionine:lysine	30	30
Methionine and cysteine:lysine	56	56
Threonine:lysine	67	67
Tryptophan:lysine	20.1	20.1
Valine:lysine	85	85
Total lysine, %	1.19	1.19
Net energy, kcal/kg	2,499	2,499
SID Lysine:NE, g/Mcal	4.19	4.19
Crude protein, %	19.9	20.0
STTD[6] Ca, %	0.62	0.62
STTD[6] P, %	0.50	0.50

[1]Lactation diets were fed from day 107 of gestation until day 18 of lactation. Diets were fed in meal form.

[2]Provided per kg of premix: 80 mg chromium; 1,653,467 IU vitamin A; 8,818 IU vitamin E; 88 mg biotin; 880 mg folic acid; 396 mg pyridoxine; 220,000 mg choline; 19,800 mg carnitine.

[3]Provided per kg of premix: 4,409,200 IU vitamin A; 551,150 IU vitamin D; 22,455 IU vitamin E; 1,764 mg vitamin K; 15 mg B12; 19,841 mg niacin; 11,023 mg pantothenic acid; 3,307 mg riboflavin.

[4]Provided per kg of premix: 73 g from Zn sulfate; 73 g Fe from iron sulfate; 22 g Mn from manganese oxide; 11 g Cu from copper sulfate; 0.2 I from calcium iodate; 0.2 Se from sodium selenite.

[5]Ronozyme HiPhos 2700, DSM Nutritional Products Inc., Parsippany, NJ.

[6]STTD = standardized total tract digestible.

Table 3-2 Chemical analysis of the diets (as-fed basis)[1]

	Added phytase, FYT/kg		
Item, %	0	1,000	3,000
Dry matter	88.43	88.03	87.94
Crude protein	19.7	20.2	20.4
Ca	0.94	0.79	0.76
P	0.66	0.54	0.54
Phytase, FYT[2]	17	1,261	3,744

[1]Diet samples were collected from each batch of feed at manufacturing from every fifth bag. Nutrient analysis was conducted on composite samples (Ward Laboratories Inc., Kearney, NE).

[2]Phytase analyzed at DSM Nutritional Products Inc., Technical Marketing Analytical Services, Belvidere, NJ.

Table 3-3 Effect of high phytase supplementation in lactation diets on sow performance[1]

	Added phytase, FYT/kg[2]				Probability, *P* =	
	0	1,000	3,000	SEM	Linear	Quadratic
Number of sows, n	36	36	37	--	--	--
Parity	2.1	2.1	2.1	1.13	0.990	0.924
Sow body weight, kg						
d 107[3]	240.2	243.9	236.2	4.89	0.452	0.418
Post-farrow	230.1	232.7	232.6	4.59	0.424	0.475
Wean	219.5	221.9	221.9	4.30	0.507	0.551
Change (farrow to wean)	-10.5	-10.6	-10.6	1.64	0.943	0.943
Sow ADFI, kg						
d 0 to 7	4.3	4.7	4.6	0.13	0.140	0.144
d 7 to 14	6.2	6.4	6.5	0.18	0.367	0.793
d 14 to wean	6.8	7.2	7.4	0.20	0.020	0.264
Farrow to wean	5.6	5.9	6.0	0.13	0.093	0.285
Farrowing duration, min[4]	398	376	351	30.0	0.226	0.873
Lactation length, d	18.1	18.3	18.1	0.18	0.586	0.366
Wean to estrus, d	4.8	4.6	4.6	1.08	0.707	0.710

[1]A total of 109 sows (DNA Genetics, Columbus, NE) and their litters were used.

[2]Ronozyme HiPhos 2700, DSM Nutritional Products Inc., Parsippany, NJ.

[3]Dietary treatments were fed from the time when sows were loaded into the farrowing room at d 107 of gestation until weaning (d 18 of lactation).

[4]Farrowing duration was determined for a total of 101 sows and excludes any sow that expelled a retained fetus 24-hours past the parturition of the initial piglet or initial time of farrowing could not be confirmed. The initiation of farrowing was classified as the birth of the first piglet and the completion of farrowing was determined by the first dispersal of placental tissues with no subsequent pigs born.

Table 3-4 Effect of high phytase supplementation in lactation diets on litter performance[1]

	Added phytase, FYT/kg[2]				Probability, *P* =	
	0	1,000	3,000	SEM	Linear	Quadratic
No. of sows	36	36	37	--	--	--
Farrowing performance						
Total born	17.4	17.8	16.2	0.68	0.135	0.316
Born alive,[3] %	91.8	90.7	91.3	1.18	0.839	0.478
Stillborn,[3] %	5.8	6.6	6.0	1.20	0.995	0.541
Mummified,[3] %	2.0	2.4	2.4	1.35	0.710	0.729
Litter count, n						
d 2[4]	14.7	15.0	13.9	1.04	0.252	0.428
Wean	12.9	13.7	13.1	1.05	0.961	0.337
Piglet survivability,[5] %	88.3	91.3	94.2	1.20	0.002	0.676
Litter weight, kg						
d 2[6]	21.0	20.9	21.2	0.60	0.760	0.816
d 7[7]	32.9	34.1	33.7	0.46	0.278	0.108
d 14[7]	55.4	58.0	56.6	1.00	0.551	0.053
Wean[7]	67.5	71.5	69.2	1.41	0.613	0.039
Litter average daily gain, g[7]	2,866	3,092	2,989	79.4	0.427	0.053
Overall litter gain, kg	46.3	50.3	48.2	1.55	0.543	0.047
Pig weight, kg						
d 2	1.4	1.5	1.4	0.04	0.794	0.346
d 7[8]	2.5	2.4	2.5	0.03	0.210	0.119
d 14[8]	4.2	4.2	4.4	0.08	0.154	0.302
Wean[8]	5.2	5.2	5.4	0.12	0.281	0.457
Pig weight gain, g[9]	3,753	3,758	3,906	124.9	0.351	0.771

[1]A total of 109 sows (DNA Genetics, Columbus, NE) and their litters were used. Treatment diets were fed starting on d 107 of gestation until weaning (d 18 of lactation).

[2]Ronozyme HiPhos 2700, DSM Nutritional Products Inc., Parsippany, NJ.

[3]Percent of total born.

[4]Cross-fostering occurred within treatment in an attempt to equalize litter size.

[5]Piglet survivability = litter count at weaning/litter count on d 2.

[6]Litters were weighed at 48 h after cross-fostering.

[7]Litter weight on d 2 was used as a covariate.

[8]Pig weight on d 2 was used as a covariate.

[9]Pig weight gain = pig weight at weaning minus pig weight at d 2.