Effect of roller mill configuration on growth performance of nursery and finishing pigs and milling characteristics[1]

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ABSTRACT: Three experiments were conducted to evaluate the effects of roller mill configuration on growth performance of nursery and finishing pigs, feed preference, and feed mill throughput. The four experimental treatments included corn ground through a roller mill using two, three, four sets of rolls in a fine-grind configuration, or four sets of rolls in a coarse grind configuration. The same roller mill was used for all configurations with the appropriate lower rolls completely open when using the two or three roll pair configurations. Across all studies, mean particle size averaged approximately 540, 435, 270, and 385 μm for the four roller mill configurations, respectively. In Exp. 1, 320 pigs (DNA 400 × 200, initially 10.7 ± 0.27 kg BW) were randomly allotted to treatments with five pigs per pen and 16 pens per treatment in a 21-d growth trial. While there were no evidence of differences observed for ADG or ADFI, pigs fed corn ground using the 4-high coarse configuration had a marginally significant ($P = 0.091$) improvement in G:F compared with those fed with the 2-high configuration, with others intermediate. In Exp. 2, 90 pigs (PIC 327 × 1050, initially 12.1 ± 0.25 kg BW) were randomly allotted to one of three diet comparisons to determine feed preference between the 2-high, 4-high fine, and 4-high coarse configurations. When given a choice, pigs consumed more ($P < 0.05$) of the diet containing corn ground through the 2-high roller mill (67%) or 4-high coarse configuration (63%) compared with corn ground through the 4-high fine configuration. In Exp. 3, 922 finishing pigs (PIC TR4 × [FAST Large white × PIC Line 2], initially 40.1 ± 0.36 kg BW) were used in a 97-d experiment with pens of pigs randomly allotted by initial BW to the same experimental treatments used in Exp. 1. There were 21 pigs per pen and 11 pens per treatment. Pigs fed corn ground with the 2-high configuration had greater ($P < 0.05$) ADG compared with those fed corn ground using the 3-high configuration. Pigs fed corn ground with the 4-high fine configuration had the poorest ($P < 0.05$) ADG. No differences were observed in G:F. Grinding rate (tonne/h) was greatest ($P < 0.05$) for the 4-high coarse configuration, while net electricity consumption (kWh/tonne) was lowest ($P < 0.05$) for the 2-high configuration and greatest for the 4-high fine configuration. In summary, nursery pig G:F tended to be greatest using the 4-high coarse configuration, and finishing pig ADG was maximized using the 2- and 4-high coarse configurations.

Key words: feed preference, finishing pigs, grinding cost, nursery pigs, particle size, roller mill

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INTRODUCTION

It is generally thought that as grain is ground to a fine mean particle size, a linear improvement in nutrient utilization and pig performance will be observed (Rojas et al., 2016). Research has demonstrated this benefit when particle size is reduced from 1,000 µm to approximately 400 µm in finishing pigs (Wondra et al., 1995b) and is thought to increase ME from increased starch digestibility as a result of greater surface area for enzymatic digestion (Rojas et al., 2016). Generally, as grains are ground to a very fine mean particle size, there becomes an increasing amount of extremely fine particles (Ganesan et al., 2008), which may affect diet palatability and flowability. Hammermills and roller mills are the primary methods used to reduce particle size due to the ability to handle a wide variety of ingredients and capability to grind to a very small particle size (Heiman and Champion, 2005); however, with a hammermill, the variation in particle size of the final ground grain can be high. By comparison, the roller mill is able to grind grain to a more consistent particle size and generally has a lower operating cost (Wondra et al., 1995a). Previously, roller mill technology could not achieve mean grain particle size below 600 µm on a consistent basis. Previous research often used a roller mill to grind coarse particle sizes due to the ability to achieve a precise target followed by grinding with a hammermill to grind to a finer particle size (Nemechek, 2016). However, recent introduction of roller mills with three or four sets of grinding rolls allow for grinding to fine particle size, while minimizing the amount of very fine particles compared with hammermill ground grain. Therefore, the objective of these experiments was to compare various roller mill configurations used to grind corn on milling characteristics, nursery pig feed preference and growth performance, and commercial finishing pig growth performance.

MATERIALS AND METHODS

General

The Kansas State University Institutional Animal Care and Use Committee approved the protocols used in these experiments. The roller mill (RMS Roller-Grinder Quadruple Pair, Harrisburg, SD) used to grind corn for all three experiments was located at the New Fashion Pork feed mill located in Estherville, IA, and used four pairs of grinding rolls. All corn used in Exp. 1 and 2 was transported to the Kansas State University O.H. Kruse Feed Technology Innovation Center for manufacturing of the complete diets. Diets used in Exp. 3 were manufactured at the New Fashion Pork feed mill (Estherville, IA). Diets in all three experiments were fed in mash form. Exp. 1 was conducted at the Kansas State University Segregated Early Weaning Facility, and Exp. 2 was conducted at the Kansas State University Swine Teaching and Research Center in Manhattan, KS. Exp. 3 was conducted at New Fashion Pork commercial research facilities located in Round Lake, MN.

In Exp. 1, each pen had tri-bar floors and contained a four-hole, dry self-feeder and a cup waterer to provide ad libitum access to feed and water. Pens (1.22 × 1.22 m) each contained five pigs and allowed approximately 0.298 m^2 per pig. In Exp. 2, pens had wire-mesh floors and contained either two 2-hole, dry self-feeders or two 4-hole, dry self-feeders balanced among comparisons and a nipple waterer to provide ad libitum access to feed and water. Pens (1.52 × 1.22 m) each contained five pigs and allowed approximately 0.371 m^2 per pig. In Exp. 3, research facilities were double-curtain-sided with completely slatted flooring and deep pits for manure storage. Each pen was equipped with a five-hole stainless steel dry self-feeder and a cup waterer for ad libitum access to feed and water. Pens (2.44 × 5.59 m) each contained 21 pigs and allowed approximately 0.650 m^2 per pig. Daily feed additions to each pen were accomplished and recorded using a robotic feeding system (FeedPro; Feedlogic Corp., Willmar, MN).

Roller Mill Specifications

Corn for treatment diets was ground using a roller mill with four sets of grinding rolls. Experimental treatments were diets with the corn fraction ground using two sets of rolls, three sets of rolls, four sets of rolls in a fine-grind configuration, or four sets of rolls in a coarse grind configuration. The same roller mill was used for all configurations with the appropriate lower rolls completely open when using the two or three roll pair configurations. The roller mill configurations for each treatment included two sets of grinding rolls with roll gaps open to 0.889 and 0.635 mm, listed from top to bottom, three sets of grinding rolls with roll gaps open to 0.889, 0.635, and 0.508 mm, four sets of grinding rolls with gaps open to 0.889, 0.635, 0.381, and 0.229 mm, and four sets of grinding rolls with roll gaps open to 1.02, 0.762, 0.762, and 0.635 mm. All grinding rolls had a 2% left spiral. The top rolls each had 2.36 corrugations/cm. The second set of grinding rolls had 3.94 corrugations/cm, while one roll had 4.72 corrugations/cm and the second roll had 5.51 corrugations/cm in set 3. The fourth set of rolls had one roll with 5.51 corrugations/cm and one roll with 6.30 corrugations/cm. Thus, the number of corrugations/cm increased from top to bottom. Roll speed differential (approx. 1.5:1) was set to create a shearing action and was 1,126 rpm for the fast roll (40.64 cm diameter sheave) and 763 rpm for the slow roll (59.94 cm diameter sheave). Corn feed rate was set based on a targeted 85% load on the roller mill, and amperage for each pair of grinding rolls was collected during grinding. In addition, the roller mill was equipped with sampling ports to allow for collection of ground corn below each set of grinding rolls.

Prior to initiation of the experiment, testing of various roller mill configurations was performed to determine experimental settings. Experimental configurations were established such that corn was ground as consistently as possible using two sets of grinding rolls, three sets of grinding rolls, four sets of grinding rolls, and a final configuration (4-high coarse), which was targeted to the particle size achieved using three sets of grinding rolls. This configuration was established to determine whether increased throughput could be achieved with an additional set of grinding rolls.

Roller Mill Data and Ground Grain Sample Collection

In addition to grinding corn used in experimental diets, batches of corn were ground on three separate occasions using the roller mill for approximately 3 h using each configuration and routed to a single bin within the feed mill. The corn was then used in production system diets, and the process was then repeated for the other configurations. This produced an accurate estimate of throughput over a longer duration of time. Grinding of corn used in treatment diets occurred on 21 dates (1 date for Exp. 1 and 2, 20 dates for Exp. 3). Throughput and electricity consumption data were collected on the roller mill on 23 separate occasions (20 dates for Exp. 3 and 3 capacity tests), and analysis of samples fed during the growth performance portion of the experiment did not include the samples from the capacity tests. Of the 21 dates when experimental diets were manufactured, corn samples were collected and analyzed on 20 of those dates. Analysis of corn ground for Exp. 1 and 2 was conducted independently of corn ground for Exp. 3. Physical analysis of corn that was fed during Exp. 3 included 19 grinding dates, and the only sample that was collected was from the collection port below the last grinding roll on 15 of those days. On the four remaining days, a sample was collected from a port beneath each set of grinding rolls for a detailed analysis of physical characteristics following each set of grinding rolls for each of the experimental configurations. In addition, corn samples were collected between every grinding roll for the three capacity tests, for a total of seven sets of samples collected between each grinding roll. Full physical characteristic analysis was conducted on all seven sets of samples collected following each grinding roll with the exception of particle size analysis and critical orifice diameter (**COD**), which was unable to be performed for one set of samples due to development of mold within the stored samples.

Electricity consumption data were collected on all grinding dates with the exception of nursery corn grinding, for a total of 23 collection dates. Gross roller mill electricity consumption was documented from the automation system output as kilowatt consumption recorded in 1-min intervals over the full duration of grinding events. Net electricity was calculated by subtracting the power required to operate the roller mill under no load (46 kW) from the gross consumption when grinding each treatment on each grinding date. Net electricity consumption per tonne (kWh/tonne) was then calculated by dividing net electricity consumption (kW) by throughput (tonne/h).

Ground Grain and Diet Physical Analysis

Particle size analysis, bulk density, angle of repose, and COD were measured on all ground corn samples at the Kansas State University Swine Lab. In addition, bulk density, angle of repose, and COD were determined for complete diets. Bulk density was determined for ground corn and complete diet using procedures previously described by Clementson et al. (2010) using mass of material contained within a pint cup (Seedburo Model 8800, Seedburo Equipment, Chicago, IL), converted to gram per liter. Briefly, the sample was poured into a funnel resting above the bulk density cup at which point a slide gate was opened allowing the grain to freely fall into the cup until it overflowed around the circumference. The funnel was then removed and a wood leveling stick was used to remove excess sample and level the sample with the top of the cup with a standardized motion. The weight of the sample in the cup was then recorded.

Particle size was determined using a 13-sieve stack with U.S. sieve numbers 6, 8, 12, 16, 20, 30, 40, 50, 70, 100, 140, 200, 270, and pan. A Ro-Tap shaker (W.S. Tyler, Mentor, OH) was used to sift the 100 g of samples for 15 min using sieve agitators including bristle sieve cleaners and rubber balls on select sieves. Particle size analysis was conducted with the addition of 0.5-g flow agent (Amorphous silica powder; Gilson Company Inc., Lewis Center, OH) per 100-g sample. Geometric mean particle size by mass (d_{gw}), the geometric standard deviation of particle diameter by mass (S_{gw}), and grain surface area (A_{st}) were calculated using the quantity of sample remaining on each screen following the shaking procedure (ASABE, 2008). Angle of repose was measured by allowing feed or grain to flow freely over a flat circular platform of a known diameter, from which the height of the resulting material was measured and diameter of the pedestal was used to calculate the angle of repose (Appel, 2005).

COD was measured using a Flowdex device (Hanson Research, Chatsworth, CA) following procedures previously described by Kalivoda et al. (2015). Briefly, 50 g of sample was measured and allowed to flow through a stainless steel funnel into a cylinder to ensure consistent flow into the cylinder between samples. The sample rested for 30 s in the cylinder, and then the bottom of the cup was opened and the sample was evaluated based on its ability to flow through an opening in a horizontal disc. The discs were 6 cm in diameter and the interior hole ranged from 4 to 34 mm. A negative result was recorded when the sample did not flow through the opening in the disc or formed a cylindrical hole with only the center material falling through the opening. A positive result was recorded when the material flowed through the disc opening forming an inverted cone shape. The procedure began with a small opening and progressively larger discs were used until a positive result was observed. If a positive result was observed, the procedure was repeated using the same disc opening size until three positive results were consecutively observed and were recorded as the COD.

Animals and Diets

In Exp. 1, pens of pigs (DNA [Columbus, NE] 400 × 200, n = 320, initially 10.7 ± 0.27 kg BW) were randomly allotted to one of four dietary treatments and fed for 21 d. There were 16 pens per treatment and five pigs per pen. The four dietary treatments used the identical corn-soybean meal-based formulation that was manufactured from the same batch of ingredients (Table 1). Experimental diets included feed with corn ground using two sets of rolls, feed with corn ground using three sets of rolls, feed with corn ground using four sets of rolls in a fine-grind configuration, and with the corn ground using four sets of rolls in a coarse grind configuration. Pig weights and feed disappearance were measured on day 0, 7, 14, and 21 to determine ADG, ADFI, and G:F.

As a follow-up to Exp. 1, 90 pigs (PIC [Hendersonville, TN] 327 × 1050, n = 90, initially 12.1 ± 0.25 kg BW) were used in a feed preference study. Pens were randomly allotted to one of three diet comparisons with six pens per comparison and five pigs per pen. Each pen contained either two 2-hole, dry self-feeders or two 4-hole, dry self-feeders balanced among comparisons with each containing one of the three treatment diets to determine feed preference over the 7-d experiment. Experimental diets included the 2-high, 4-high fine, and 4-high coarse manufactured diets with identical formulations to Exp. 1 and used a common batch of ground corn. Diet comparisons tested included the 2-high vs. 4-high fine, 2-high vs. 4-high coarse, and 4-high fine vs. 4-high coarse. Feeders were rotated daily within each pen to reduce any effect of feeder location within pen on intake. Feeders were weighed on day 0, 2, 4, and 7 to determine ADFI of each diet consumed and percentage of total ADFI consumed of each diet, and pig weights were calculated on day 0 and 7 of the trial to determine ADG and G:F.

In Exp. 3, a total of 922 pigs (PIC [Hendersonville, TN] TR4 × [FAST {Saskatoon, SK} Large white × PIC Landrace], initially 40.1 ± 0.36 kg BW) were used in a 97-d experiment. Pens were randomly allotted to one of four experimental treatments by initial BW with 11 pens per treatment with 20 or 21 pigs per pen. All diets were the same corn-soybean meal-based diet containing 20% distiller's dried grains with solubles (**DDGS**). Experimental treatments included the corn fraction of the diets ground using identical roller mill configurations as Exp. 1 and 2. Diets were fed in a five-phase feeding program, and fed from 32 to 45, 45 to 64, 64 to 82, 82 to 105, and 105 to 127 kg (Table 2). Pigs were weighed and feed disappearance was measured on day 0, 14, 28, 43, 56, 75, 83, and 97 to calculate ADG, ADFI, and G:F. For Exp. 1 and 3, caloric efficiencies (ME and NE basis) were calculated by multiplying total feed intake × energy content of the diet (kcal/kg) and dividing by total gain. On day 83 of the trial, pens were weighed and the six heaviest pigs from each pen were removed and transported

Table 1. Diet composition and chemical analysis for Exp. 1 and 2 (as-fed basis)[1,2]

Item	Exp. 1 and 2
Ingredient, %	
Corn	63.75
Soybean meal (47.7% CP)	32.85
Monocalcium phosphate (21.5% P)	1.10
Limestone	0.98
Salt	0.35
L-Lys HCl	0.30
DL-Met	0.12
L-Thr	0.12
Vitamin premix[3]	0.25
Trace mineral premix[4]	0.15
Phytase[5]	0.015
Total	100
Calculated analysis[6]	
Standard ileal digestible (SID) amino acids, %	
Lys	1.22
Ile:Lys	63
Leu:Lys	129
Met:Lys	33
Met & Cys:Lys	57
Thr:Lys	63
Trp:Lys	19
Val:Lys	69
Total Lys, %	1.37
ME, kcal/kg	3,324
NE, kcal/kg	2,408
SID Lys:ME, g/Mcal	3.73
SID Lys:NE, g/Mcal	5.07
CP, %	21.4
Ca, %	0.70
P, %	0.64
STTP P, %	0.47
Chemical analysis[7]	
DM, %	89.6
CP, %	20.8
Ca, %	0.77
P, %	0.61

[1]Experiment 1 treatment diets were fed to 320 pigs (DNA [Columbus, NE] 400 × 200, initial BW 10.7 ± 0.27 kg) for 21 d.

[2]Experiment 2 treatment diets were fed to 90 pigs (PIC [Hendersonville, TN] 327 × 1050, initial BW 12.1 ± 0.25 kg) for 7 d.

[3]Premix provided per kilogram of premix: 4,409,249 IU vitamin A; 551,156 IU vitamin D3; 17,637 IU vitamin E; 1,764 mg vitamin K; 15.4 mg vitamin B12; 19,842 mg niacin; 11,023 mg pantothenic acid; and 3,307 mg riboflavin.

[4]Premix provided per kilogram of premix: 110 g Fe from iron sulfate; 110 g Zn from zinc sulfate; 26.4 g Mn from manganese oxide; 11 g Cu from copper sulfate; 198 mg I from calcium iodate; and 198 mg Se from sodium selenite.

[5]HiPhos 2700 (DSM Nutritional Products, Inc., Parsippany, NJ) provided an estimated release of 0.09% STTD P.

[6]NRC (2012).

[7]A composite sample collected directly from multiple feeders per treatment within experiment, subsampled, and submitted to Ward Laboratories (Kearney, NE) for analysis. Analyzed values were then averaged among treatments and experiments (n = 7 values for each reported value).

550 km to Triumph Foods (St Joseph, MO) for harvest and collection of carcass data. On day 97, the remaining pigs were transported to Triumph Foods for harvest. Carcass yield was calculated using live weight at the farm and HCW at the plant. At the plant, backfat and loin depth were measured, while percentage lean was calculated using a proprietary formula using HCW, backfat depth, and loin depth.

Chemical Analysis

For all three experiments, complete diet samples were collected from multiple feeders within treatment, combined within phase when applicable, and subsampled for analysis. All feed samples were analyzed (Ward Laboratories; Kearney, NE) for DM (AOAC 934.01, 2006), CP (AOAC 990.03, 2006), ether extract (AOAC 920.39 A, 2006), ash (AOAC 942.05, 2006), Ca (AOAC 965.14/985.01, 2006), P (AOAC 965.17/985.01, 2006), starch (AOAC 996.11, 2006), and ADF (Van Soest et al., 1991). Additionally, diet samples from Exp. 1 and 2 were analyzed for crude fiber (AOAC 978.10, 2006), from which nitrogen-free extract (NFE = 100 – CP – Ash – ether extract − CF) was calculated.

Statistical Analysis

Data were analyzed as a completely randomized design using PROC GLIMMIX in SAS (SAS Institute, Inc., Cary, NC) with pen as the experimental unit in Exp. 1. In Exp. 2, feeder within pen was the experimental unit, and pen was included in the model as a random effect. The LSMEANS procedure of SAS was used to evaluate pen means (Exp. 1) and within pen mean difference in ADFI, which was expressed as a percentage of the total consumed for each diet (Exp. 2). In Exp. 3, pens of pigs were blocked by initial BW and allotted to treatment. Data were analyzed as a randomized complete block design using PROC GLIMMIX with pen as the experimental unit. Hot carcass weight was standardized using a covariate for carcass characteristics including percentage lean, loin depth, and backfat depth.

Roller mill electricity consumption, throughput, and analysis of ground corn samples were analyzed using PROC GLIMMIX with roller mill configuration within grinding day as the experimental unit and grinding date included in the statistical model as a random effect. For analysis of ground corn samples collected following each grinding roll, data were analyzed as an incomplete 4 × 4 factorial arrangement with four roller mill configurations and four roll locations, void of one configuration ×

Table 2. Diet composition, Exp. 3 (as-fed basis)[1]

Item	BW range, kg				
	32 to 45	45 to 64	64 to 82	82 to 105	105 to 127
Ingredient, %					
Corn	57.81	62.02	65.68	69.05	70.99
Soybean meal (47.5% CP)	19.41	15.52	12.08	8.66	6.91
DDGS[2]	20.00	20.00	20.00	20.00	20.00
Dicalcium phosphate (18.8% P)	0.45	0.25	0.15	—	—
Limestone	1.20	1.15	1.10	1.30	1.20
Salt	0.35	0.35	0.35	0.35	0.35
L-Lys HCl	0.45	0.43	0.40	0.40	0.35
L-Thr	0.08	0.06	0.04	0.05	0.04
L-Trp	0.03	0.03	0.02	0.03	0.02
MHA dry (Met)	0.08	0.05	0.03	0.02	—
Vitamin and mineral premix[3,4]	0.15	0.15	0.15	0.15	0.15
Total	100	100	100	100	100
Calculated analysis[5]					
Standard ileal digestible (SID) amino acids, %					
Lys	1.02	0.91	0.81	0.73	0.65
Ile:Lys	62	62	63	62	65
Leu:Lys	153	163	174	183	200
Met:Lys	31	31	31	31	31
Met & Cys:Lys	56	57	58	60	62
Thr:Lys	62	62	62	63	66
Trp:Lys	18.5	18.5	18.5	18.5	18.5
Val:Lys	69	71	73	73	78
Total Lys	1.14	1.02	0.91	0.83	0.74
ME, kcal/kg	3,211	3,223	3,232	3,234	3,239
NE, kcal/kg	2,462	2,491	2,515	2,533	2,546
SID Lys:ME, g/Mcal	3.18	2.82	2.51	2.26	2.01
SID Lys:NE, g/Mcal	4.14	3.65	3.22	2.88	2.55
CP, %	19.0	17.4	15.9	14.6	13.8
Ca, %	0.67	0.58	0.52	0.53	0.49
P, %	0.54	0.49	0.46	0.42	0.42
STTD P, %	0.40	0.36	0.34	0.31	0.31

[1]A total of 922 pigs (PIC [Hendersonville, TN] TR4 × [FAST {Saskatoon, SK} Large white × PIC Landrace], initial BW 40.1 ± 0.36 kg) were used in a 97-d growth experiment in a five-phase feeding program.

[2]DDGS = distiller's dried grains with solubles.

[3]VTM premix provided an estimated release of 0.11% STTD P.

[4]Premix provided per kilogram of premix: 4,116,034 IU vitamin A; 588,635 IU vitamin D3; 26,455 IU vitamin E; 1,470 mg vitamin K; 16.2 mg vitamin B12; 17,637 mg niacin; 11,759 mg pantothenic acid; 5,880 mg riboflavin; 83 g Fe from iron sulfate; 60 g Zn from zinc sulfate; 5.0 g Mn from manganese oxide; 108 g Cu from copper sulfate; 200 mg I from calcium iodate; and 200 mg Se from sodium selenite.

[5]NRC (2012).

roll location combination (2-high configuration, sample following third roll), which was not collected. Degrees of freedom were estimated using the Kenward–Rogers approach. Statistical assumptions were assessed using standard diagnostics on Studentized residuals, and statistical models were expanded to account for heterogeneous residual variance when necessary as described by Goncalves et al. (2016). Results were considered significant at $P \leq 0.05$ and marginally significant between $P > 0.05$ and $P \leq 0.10$.

RESULTS

Chemical Analysis

Chemical analysis of diets fed in Exp. 1 and 2 (Table 3) and Exp. 3 (Table 4) resulted in no notable differences among treatments.

Milling Characteristics

Corn ground using the 4-high fine configuration resulted in the slowest ($P < 0.001$) production rate

Table 3. Chemical analysis of diets, Exp. 3 (as-fed basis)[1]

	Roller mill configuration[2]			
Item, %	2-High	3-High	4-High fine	4-High coarse
Phase 1				
DM	88.91	88.98	88.48	88.59
CP	18.7	19.6	18.1	19.0
ADF	5.5	6.4	6.1	5.8
Ca	0.79	0.62	0.60	0.76
P	0.51	0.48	0.49	0.5
Ether extract	3.4	3.4	3.6	3.2
Ash	4.6	4.1	4.2	4.3
Starch	34.1	33.9	35.7	37.2
Phase 2				
DM	87.87	88.19	87.63	87.88
CP	15.6	15.4	16.6	15.7
ADF	5.2	5.4	5.7	5.4
Ca	0.64	0.63	0.70	0.56
P	0.44	0.43	0.44	0.44
Ether extract	3.3	3.4	3.3	3.4
Ash	4.0	3.7	4.0	3.5
Starch	43.1	41.9	41.4	39.7
Phase 3				
DM	88.02	88.01	87.95	88.1
CP	15.9	15.7	16.4	16.6
ADF	5.8	4.7	5.7	6.0
Ca	0.71	0.54	0.56	0.57
P	0.43	0.45	0.44	0.44
Ether extract	3.1	3.1	3.2	3.4
Ash	3.8	3.6	3.6	3.3
Starch	43.9	40.9	39.9	39.9
Phase 4				
DM	88.64	89.54	88.36	88.33
CP	14.9	14.0	13.5	14.5
ADF	3.7	3.1	4.1	3.8
Ca	0.59	0.48	0.51	0.50
P	0.43	0.41	0.41	0.41
Ether extract	4.1	3.4	3.6	3.7
Ash	3.6	3.2	3.3	3.3
Starch	40.4	40.0	41.2	42.5
Phase 5				
DM	89.92	87.65	88.96	88.44
CP	14.3	14.4	13.1	13.4
ADF	3.8	4.2	3.4	3.4
Ca	0.60	0.59	0.58	0.60
P	0.41	0.43	0.40	0.43
Ether extract	3.4	3.8	3.2	3.6
Ash	3.4	3.4	3.3	3.5
Starch	45.1	41.5	45.5	42.0

[1]A composite sample collected directly from multiple feeders per treatment per phase, subsampled, and submitted to Ward Laboratories (Kearney, NE) for analysis.

[2]Corn was ground using two sets of rolls, three sets of rolls, four sets of rolls in a fine-grind configuration, or four sets of rolls in a coarse configuration.

(tonne/h), followed by the 3-high configuration, 2-high configuration, and the 4-high coarse having the greatest production rate (Table 4). Corn ground using the 2-high configuration resulted in the lowest ($P < 0.001$) net electrical energy consumption/tonne of ground corn, followed by the 3-high configuration, 4-high coarse configuration, and the 4-high fine configuration that resulted in the greatest grinding net electricity consumption per tonne ground corn. Within the range of particle sizes generated using the four roller mill configurations in the current study, each 100 µm reduction in particle size increased net electricity consumption per tonne by approximately 0.35 kWh/tonne.

Physical Analysis—Ground Corn and Diets

Corn used in Exp. 1 and 2 ground using the 3-high configuration and the 4-high coarse configuration had similar mean particle size (394 and 403 µm, respectively) and standard deviation (2.73 vs. 2.81, respectively; Table 5). The 4-high fine configuration produced the finest particle size corn, as expected, and also had the lowest standard deviation (267, 2.57 µm, respectively). As particle size was reduced, surface area, expressed as centimeter square per gram, increased. COD was greatest for the 4-high configurations (267 and 403 µm), whereas the 2-high configuration (525 µm) had an improved COD, and the 3-high configuration (394 µm) had the most desirable (lowest) COD flowability. The 4-high fine configuration (267 µm) had the least desirable ($P < 0.001$) angle of repose flowability score, whereas the 2- and 3-high configurations (525 and 394 µm, respectively) produced the most desirable angle of repose flowability, with the 4-high coarse configuration (403 µm) intermediate. Corn ground using the 4-high fine (267 µm) and 3-high configuration (394 µm) had the lowest ($P < 0.001$) bulk density, whereas the 2-high (525 µm) and 4-high coarse (403 µm) configurations produced ground corn with the heaviest bulk density.

Physical analysis of ground corn fed in Exp. 3 was similar to Exp. 1 and 2 as expected. Corn ground using the 2-high configuration (561 µm) had the greatest ($P < 0.001$) particle size, followed by a reduction in particle size for the 3-high configuration (473 µm), further reduction for the 4-high coarse configuration, and the 4-high fine configuration having the finest particle size (561, 473, 371, and 285 µm). Corn ground using the 4-high fine configuration (285 µm) had the lowest ($P < 0.001$) standard deviation compared with all other treatments, and the 2-high configuration (561 µm) ground had the greatest, with the 3-high (473 µm) and 4-high coarse (371 µm) configurations being intermediate. The ground corn surface area

Table 4. Roller mill electricity consumption, Exp. 1–3[1]

Item	Roller mill configuration[2]					
	2-High	3-High	4-High fine	4-High coarse	SEM	Probability, *P*
Grinding rate, tonne/h	12.09[b]	10.89[c]	7.41[d]	13.06[a]	0.357	<0.001
Net electricity consumption, kWh/tonne[3]	1.11[d]	1.49[c]	2.17[a]	1.59[b]	0.033	<0.001

[1]Data collection occurred on 23 dates (20 diet manufacture dates, 3 capacity tests).

[2]Corn was ground using two sets of rolls, three sets of rolls, four sets of rolls in a fine-grind configuration, or four sets of rolls in a coarse configuration.

[3]Net electricity consumption = Net kW/throughput. Net kW = gross kW – kW required to operate roller mill when empty. Gross and tare kW values determined from automation system output in 1-min intervals for full duration of each grinding event.

[a–d]Means within row without common superscript differ ($P < 0.05$).

Table 5. Physical analysis of ground corn used in growth trials, Exp. 1–3[1]

Item	Roller mill configuration[2]					
	2-High	3-High	4-High fine	4-High coarse	SEM	Probability, *P*
Exp. 1 and 2						
Particle size (d_{gw}), µm[3]	525	394	267	403	—	—
Standard deviation (S_{gw}), µm	3.14	2.73	2.57	2.81	—	—
Surface area, cm²/g[4]	166.7	190.9	264.9	192.6	—	—
Critical orifice diameter, mm[5]	24	22	26	26	—	—
Angle of repose, degrees[6]	52.0[c]	52.8[c]	57.6[a]	54.3[b]	0.41	<0.001
Bulk density, g/L[7]	509.2[a]	488.7[b]	485.9[b]	507.6[a]	1.51	<0.001
Exp. 3						
Particle size (d_{gw}), µm	561[a]	473[b]	285[d]	371[c]	10.7	<0.001
Standard deviation (S_{gw}), µm	3.04[a]	2.96[b]	2.58[c]	2.97[b]	0.037	<0.001
Surface area, cm²/g	151.8[d]	175.9[c]	247.9[a]	224.0[b]	6.13	<0.001
Critical orifice diameter, mm	23.3[b]	23.4[b]	25.6[a]	25.9[a]	0.49	<0.001
Angle of repose, degrees	48.0[d]	50.5[c]	54.8[a]	53.7[b]	0.33	<0.001
Bulk density, g/L	516.4[a]	508.3[b]	483.2[c]	509.3[b]	4.72	<0.001

[1]Analysis included only samples of ground corn which were fed during the growth trials and collected at the bottom of the roller mill (1 grinding date for Exp. 1 and 2 corn; 19 grinding dates for Exp. 3).

[2]Corn was ground using two sets of rolls, three sets of rolls, four sets of rolls in a fine-grind configuration, or four sets of rolls in a coarse configuration.

[3]Particle size was determined using a Ro-Tap Shaker (W.S. Tyler) with 13 sieves and a pan with a shake time of 15 min, using 0.50 g amorphous silica powder (Gilson Company, Inc., Lewis Center, OH) added as sieving agent to 100.0 g grain sample.

[4]ASABE (2008) Standard S319.4.

[5]Critical orifice diameter measured using Flowdex (Hanson Research) and represents smallest diameter disc in which 50 g of material freely flows on three consecutive attempts.

[6]Samples ran in triplicate, thus $n = 3$ for each treatment.

[7]Samples ran in quintuplicate, thus $n = 5$ for each treatment.

[a–d]Means within row without common superscript differ ($P < 0.05$).

—Analysis was only performed on the single sample; therefore, SEM and *P* values were not to be determined.

was greatest ($P < 0.001$) for the 4-high fine configuration (285 µm), followed by the 4-high coarse (371 µm), 3-high (473 µm), and finally the 2-high (561 µm) configuration that produced ground corn with the lowest surface area. The 2-high (561 µm) and 3-high (473 µm) configurations had more desirable ($P < 0.001$) COD flowability scores relative to the 4-high configurations. Corn ground using the 2-high configuration (561 µm) had the most desirable ($P < 0.05$) angle of repose flowability, followed by the 3-high (473 µm), 4-high coarse (371 µm), and the 4-high fine (285 µm) configuration that produced the least desirable angle of repose flowability. Corn ground using the 4-high fine (285 µm) had the lowest ($P < 0.05$) bulk density, followed by the 3-high (473 µm) and 4-high coarse (371 µm) configurations, while the 2-high configuration produced ground corn with the greatest bulk density. As grain progresses through additional sets of grinding rolls within configuration, a reduction ($P < 0.05$) of particle size and standard deviation was observed as expected (Table 6) in addition to

Table 6. Characterization of roller mill ground corn, Exp. 3[1]

Item	Roller mill configuration[2] 2-High[3]	3-High	4-High fine	4-High coarse	SEM	Probability, P Treatment	Location	Treatment × Location
Particle size (d_{gw}), µm[4]								
Roll set 1	657[b]	716[a,b]	659[b]	741[a]	25.8	<0.001	<0.001	<0.001
Roll set 2	518[c,d,e]	495[d,e]	501[d,e]	543[c,d]				
Roll set 3	—	397[g]	337[h]	425[f,g]				
Roll set 4	574[c]	459[e,f]	295[h]	416[f,g]				
Standard deviation (S_{gw}), µm								
Roll set 1	3.98[b]	3.99[a,b]	4.12[a]	4.05[a,b]	0.084	<0.001	0.002	<0.001
Roll set 2	3.15[d,e]	3.27[c,d]	3.30[c]	3.34[c]				
Roll set 3	—	3.06[e,f]	3.02[f,g]	3.24[c,d]				
Roll set 4	3.02[f,g]	2.81[h]	2.59[i]	2.90[g,h]				
Surface area, cm²/g[5]								
Roll set 1	181.9[d,e]	166.2[e,f]	191.3[c,d]	166.0[e,f]	10.70	0.001	<0.001	<0.001
Roll set 2	171.9[d,e,f]	187.2[d,e]	187.2[d,e]	175.0[d,e]				
Roll set 3	—	215.7[b,c]	249.9[a]	214.4[b,c]				
Roll set 4	148.1[f]	177.2[d,e]	234.7[a,b]	194.1[c,d]				
Critical orifice diameter, mm[6]								
Roll set 1	26.3[a,b]	25.3[a,b,c,d]	26.7[a]	26.3[a,b]	0.857	0.100	0.005	<0.001
Roll set 2	22.7[f,g,h]	24.0[d,e,f,g]	23.0[e,f,g,h]	24.3[c,d,e,f]				
Roll set 3	—	23.7[d,e,f,g]	26.0[a,b,c]	25.0[a,b,c,d]				
Roll set 4	22.3[g,h]	21.3[h]	24.3[c,d,e,f]	24.7[b,c,d,e]				
Angle of repose, degrees								
Roll set 1	47.9[g]	48.3[f,g]	48.4[e,f,g]	48.2[g]	0.63	<0.001	<0.001	<0.001
Roll set 2	48.9[d,e,f,g]	49.9[d,e,f]	49.3[d,e,f,g]	50.2[d]				
Roll set 3	—	52.0[c]	54.6[a,b]	53.0[b,c]				
Roll set 4	48.4[f,g]	50.1[d,e]	55.1[a]	53.1[b,c]				
Bulk density, g/L								
Roll set 1	544.6[a]	546.5[a]	545.9[a]	548.6[a]	6.49	0.006	<0.001	<0.001
Roll set 2	524.9[b]	517.3[b,c]	519.1[b]	522.5[b]				
Roll set 3	—	502.2[d,e]	500.8[d,e]	515.0[b,c]				
Roll set 4	508.3[c,d]	497.9[e]	480.7[f]	504.2[d,e]				

[1]Analysis included only samples collected on dates of manufacture that collected samples below each grinding roll (seven grinding dates – seven samples for bulk density and angle of repose, six samples for remainder of physical characteristic measurements).

[2]Corn was ground using two sets of rolls, three sets of rolls, four sets of rolls in a fine-grind configuration, or four sets of rolls in a coarse configuration.

[3]Samples were not collected following third grinding roll for the 2-high configuration.

[4]Particle size was determined using a Ro-Tap Shaker (W.S. Tyler) with 13 sieves and a pan with a shake time of 15 min, using 0.50 g amorphous silica powder (Gilson Company, Inc., Lewis Center, OH) added as sieving agent to 100.0 g grain sample.

[5]ASABE (2008) Standard S319.4.

[6]Critical orifice diameter measured using Flowdex (Hanson Research) and represents smallest diameter disc in which 50 g of material freely flows on three consecutive attempts.

[a–i]Means within item without common superscripts differ ($P < 0.05$).

changes in surface area, COD, angle of repose, and bulk density. When physical characteristics of complete diets were analyzed (Table 7), results closely reflected trends observed in analysis of ground corn as expected.

Growth and Carcass Characteristics

In Exp. 1, there was no evidence of a difference ($P > 0.10$) in ADG, ADFI, or caloric efficiency among pigs fed any of the different roller mill configurations (Table 8). Pigs fed corn ground with the 4-high coarse configuration (403 µm) had marginally significant increased ($P = 0.091$) G:F compared with those fed corn ground with the 2-high configuration (525 µm; 0.667 vs. 0.645, respectively) with others intermediate. In Exp. 2, pigs consumed a greater portion of their total intake (67%; $P < 0.05$) from the diet with corn ground using the 2-high configuration (525 µm) compared with the 4-high fine configuration (33%; 267 µm; Table 9). There was no difference ($P > 0.10$) in feed consumption

Table 7. Physical analysis of diets, Exp. 3[1]

	Roller mill configuration[2]					
Item	2-High	3-High	4-High fine	4-High coarse	SEM	Probability, *P*
Exp. 1						
Critical orifice diameter, mm[3]	24	24	26	24	—	—
Angle of repose, degrees	52.1[d]	54.1[c]	57.1[a]	55.8[b]	0.49	<0.001
Bulk density, g/L	603.9[a]	587.0[c]	588.8[c]	598.8[b]	1.28	<0.001
Exp. 2						
Critical orifice diameter, mm	24	—	28	26	—	—
Angle of repose, degrees	50.4[b]	—	57.0[a]	52.1[b]	0.65	<0.001
Bulk density, g/L	617.8[a]	—	605.3[c]	609.5[b]	0.74	<0.001
Exp. 3						
Overall, phases 1–5						
Critical orifice diameter, mm	23.4	23.0	27.0	24.6	2.17	<0.114
Angle of repose, degrees	50.6[c]	52.4[b,c]	54.5[a]	52.7[a,b]	0.64	<0.001
Bulk density, g/L	541.6[a]	534.4[a,b]	528.0[b]	535.9[a,b]	3.33	<0.044
Phase 1						
Critical orifice diameter, mm	20	20	26	24	—	—
Angle of repose, degrees	48.6[b]	49.3[b]	50.3[a]	50.4[a]	0.31	<0.001
Bulk density, g/L	565.6[a]	561.1[b]	557.8[c]	565.3[a]	1.09	<0.001
Phase 2						
Critical orifice diameter, mm	26	28	30	26	—	—
Angle of repose, degrees	53.1[c]	54.6[b]	56.3[a]	52.8[c]	0.47	<0.001
Bulk density, g/L	547.5[a]	530.2[d]	534.9[c]	539.7[b]	1.04	<0.001
Phase 3						
Critical orifice diameter, mm	28	28	28	26	—	—
Angle of repose, degrees	52.6[c]	56.3[a]	57.0[a]	53.4[b]	0.27	<0.001
Bulk density, g/L	538.5[a]	529.9[c]	528.7[c]	535.6[b]	0.79	<0.001
Phase 4						
Critical orifice diameter, mm	22	22	28	26	—	—
Angle of repose, degrees	46.8[c]	49.5[b]	53.9[a]	53.4[a]	0.32	<0.001
Bulk density, g/L	538.5[a]	525.8[b]	514.6[d]	518.2[c]	0.73	<0.001
Phase 5						
Critical orifice diameter, mm	28	24	30	28	—	—
Angle of repose, degrees	51.8[c]	52.0[c]	54.8[a]	53.3[b]	0.25	<0.001
Bulk density, g/L	518.2[c]	525.0[a]	504.3[d]	520.7[b]	0.77	<0.001

[1]A composite sample collected directly from all feeders per treatment was used for analysis.

[2]Corn was ground using two sets of rolls, three sets of rolls, four sets of rolls in a fine-grind configuration, or four sets of rolls in a coarse configuration.

[3]Critical orifice diameter measured using Flowdex (Hanson Research) and represents smallest diameter disc in which 50 g of material freely flows on three consecutive attempts.

[a–d]Means within row without common superscripts differ ($P < 0.05$).

—Analysis was only performed on the single sample; therefore, SEM and *P* values were not to be determined.

between the pigs fed the diet containing 2-high roller mill ground corn (525 µm) and the diet with corn from the 4-high roller mill in a coarse configuration (403 µm; 50.3 vs. 49.7%, respectively). Pigs consumed more (63%; $P < 0.05$) of the diet manufactured using corn ground using the 4-high coarse configuration (403 µm) relative to the 4-high fine-grind configuration (267 µm; 37%).

In Exp. 3, from day 0 to 56, pigs fed diets containing corn ground with the 2-high roller mill configuration (561 µm) had greater ($P < 0.05$) ADG compared with pigs fed corn ground using the other configurations (Table 10). Pigs fed diets containing corn ground with the 2-high (561 µm) and 3-high (473 µm) roller mill configuration also had increased ($P < 0.05$) ADFI compared with pigs fed diets containing corn ground using the 4-high fine configuration (285 µm), with those fed corn ground using the 4-high coarse configuration (371 µm) being intermediate. There were no differences ($P > 0.10$) in G:F among roller mill configurations for the grower period.

From day 56 to 97, pigs fed diets containing corn ground with the 4-high fine configuration

Table 8. Effects of roller mill configuration on growth performance in nursery pigs, Exp. 1[1]

	Roller mill configuration[2]					
Item	2-High	3-High	4-High fine	4-High coarse	SEM	Probability, *P*
BW, kg						
Day 0	10.7	10.7	10.7	10.7	0.27	<1.000
Day 21	23.3	23.3	23.2	23.3	0.56	<0.998
Day 0 to 21						
ADG, kg	0.60	0.60	0.58	0.60	0.011	<0.474
ADFI, kg	0.93	0.92	0.90	0.90	0.024	<0.317
G:F	0.645[b]	0.651[a,b]	0.649[a,b]	0.667[a]	0.0083	<0.091
Caloric efficiency[3]						
ME, kcal/kg gain	5,079	5,032	5,046	4,916	64.6	<0.108
NE, kcal/kg gain	3,737	3,703	3,713	3,618	47.6	<0.108

[1]A total of 320 nursery pigs (DNA [Columbus, NE] 400 × 200, initial BW 10.7 ± 0.27 kg) were used in a 21-d study with five pigs per pen and 16 replications per treatment.

[2]Corn used in diets was ground using two sets of rolls, three sets of rolls, four sets of rolls in a fine-grind configuration, and four sets of rolls in a coarse configuration.

[3]Caloric efficiency is expressed as kcal/kg gain, using energy values for ME and NE from NRC (2012).

[a,b]Means within row without common superscript differ ($P < 0.05$).

Table 9. Effects of roller mill configuration on feed intake preference in nursery pigs, Exp. 2[1,2,3]

Item	2-High	4-High fine	4-High coarse	SEM	Probability, *P*
ADFI, kg					
Comparison 1	0.52	0.26	—	0.032	<0.001
Comparison 2	0.40	—	0.39	0.026	<0.779
Comparison 3	—	0.29	0.50	0.038	<0.003
ADFI, %[4]					
Comparison 1	67.0	33.0	—	3.88	<0.001
Comparison 2	50.3	—	49.7	2.95	<0.882
Comparison 3	—	37.1	62.9	3.91	<0.001

[1]A total of 90 pigs (PIC [Hendersonville, TN] 327 × 1050, initial BW 12.1 ± 0.25 kg) were used in a 7-d preference trial with five pigs per pen and six replications per comparison.

[2]Corn used in diets was ground using two sets of rolls, three sets of rolls, four sets of rolls in a fine-grind configuration, and four sets of rolls in a coarse configuration.

[3]Feeders were rotated once daily within each pen to eliminate any location effects of feeder.

[4]ADFI, % is a percentage of total feed intake for each treatment within a comparison.

(285 µm) had the poorest ADG ($P < 0.05$), with no evidence of a difference among the other configurations. Pigs fed diets containing corn ground with the 2-high configuration (561 µm) had the greatest ($P < 0.05$) ADFI, followed by the 3-high (473 µm) and 4-high coarse (371 µm) configurations, and the 4-high fine configuration (285 µm) resulted in the lowest ($P < 0.05$) ADFI. There was a marginally significant ($P = 0.071$) treatment effect for G:F, with pigs fed diets ground with the 4-high coarse configuration (371 µm) having increased ($P < 0.05$) G:F compared with the 2-high configuration (561 µm), with the 3- and 4-high fine configurations (473 and 285 µm, respectively) being intermediate. Overall (day 0 to 97), pigs fed diets containing corn ground with the 2-high (561 µm) and the 4-high coarse configuration (371 µm) had the greatest ADG ($P < 0.05$), followed by the 3-high configuration (473 µm), which did not significantly differ from the 4-high coarse configuration (371 µm), and the 4-high fine configuration (285 µm) had the lowest ($P < 0.05$) ADG. Pigs fed diets with corn ground using the 2-high configuration (561 µm) had the greatest ($P < 0.05$) ADFI, followed by the 3- and 4-high coarse configurations (473 and 371 µm, respectively), and pigs fed corn ground with the 4-high fine configuration (285 µm) had the lowest ($P < 0.05$) ADFI. There was no evidence of differences ($P > 0.10$) in G:F or caloric efficiency among roller mill configurations. Pigs fed diets containing corn ground with the 2-high configuration (561 µm) had greater ($P < 0.05$) final

Table 10. Effects of roller mill configuration on growth performance of finishing pigs, Exp. 3[1]

	Roller mill configuration[2]					
Item	2-Hhigh	3-Hhigh	4-High fine	4-High coarse	SEM	Probability, *P*
BW, kg						
Day 0	40.1	40.1	40.1	40.1	0.36	<1.000
Day 56	97.3[a]	95.7[b]	95.0[b]	95.6[b]	0.51	<0.004
Day 97	132.3[a]	130.3[a,b]	128.0[b]	130.4[a,b]	0.93	<0.022
Day 0 to 56						
ADG, kg	1.01[a]	0.99[b]	0.97[b]	0.99[b]	0.006	<0.003
ADFI, kg	2.53[a]	2.49[a]	2.43[b]	2.48[a,b]	0.019	<0.007
G:F	0.398	0.396	0.400	0.399	0.0023	<0.758
Day 56 to 97						
ADG, kg	0.95[a]	0.94[a]	0.89[b]	0.94[a]	0.013	<0.005
ADFI, kg	3.24[a]	3.11[b]	2.98[c]	3.11[b]	0.035	<0.001
G:F	0.294[b]	0.301[a,b]	0.299[a,b]	0.303[a]	0.0024	<0.071
Day 0 to 97						
ADG, kg	0.99[a]	0.97[b]	0.94[c]	0.97[a,b]	0.007	<0.001
ADFI, kg	2.81[a]	2.73[b]	2.65[c]	2.73[b]	0.021	<0.001
G:F	0.351	0.354	0.355	0.356	0.0017	<0.152
Caloric efficiency[3]						
ME	9,206	9,135	9,094	9,084	43.3	<0.145
NE	7,180	7,125	7,092	7,085	33.8	<0.136
Carcass characteristics[4]						
HCW, kg	95.5[a]	94.3[a,b]	92.7[b]	93.9[a,b]	0.68	<0.036
Carcass yield, %	72.18	71.89	72.65	72.55	0.497	<0.562
Backfat, mm	19.85	20.22	19.72	20.37	0.338	<0.367
Loin depth, mm	59.2	58.8	60.3	59.5	0.88	<0.559
Lean, %[6]	52.41	52.20	52.64	52.22	0.256	<0.472

[1]A total of 922 finisher pigs (PIC [Hendersonville, TN] TR4 × [FAST {Saskatoon, SK} Large white × PIC Landrace], initial BW 40.1 ± 0.36 kg) were used in a study with 21 pigs per pen and 11 replications per treatment.

[2]Corn was ground using two sets of rolls, three sets of rolls, four sets of rolls in a fine-grind configuration, or four sets of rolls in a coarse configuration.

[3]Caloric efficiency is expressed as kcal/kg gain, using energy values for ME and NE from NRC (2012).

[4]The largest six pigs were marketed from each pen on day 83. All remaining pigs were marketed from each pen on day 97. Carcass characteristics other than yield were adjusted by using HCW as a covariate.

[a–c]Means within row without common superscript differ ($P < 0.05$).

BW and HCW than pigs fed diets containing corn manufactured with the 4-high fine configuration (285 µm). There was no evidence of differences ($P > 0.10$) in carcass yield, backfat, loin depth, or percentage lean among roller mill configurations.

DISCUSSION

The use of roller mills to process cereal grains has been used for many years (Heiman and Champion, 2005), and the technology and capabilities of these machines have continued to evolve and improve. One of the unique aspects of using a roller mill originates with the grinding mechanism. Traditional roller mills set the roll speed equally for each roll within a set of grinding rolls, which would effectively crimp the grain. However, when the roll speed is offset so one roll is rotating more rapidly than the other, the grooves within the rolls allow for a shearing action that creates a fine, uniform finished product (Heiman and Champion, 2005). Hammermills reduce particle size by the impact of the grain against the moving hammer and forcing the particles through a screen with a specific opening diameter specific to the desired particle size. Due to this mechanism, the variation in the final ground corn particle size is typically greater as evidenced by a wider distribution of mass remaining on each sieve following particle size analysis. Until recently, feed manufacturers wishing to reduce the mean particle size below approximately 600 µm found it necessary to use a hammermill. However, the addition of third and fourth roll sets have allowed the mean particle size to be decreased more than what was previously possible, producing a very finely ground, consistent product (Heiman and Champion, 2005).

Generally as the mean particle size of grain is reduced, a greater amount of energy is required and production rate decreases (Hancock and Behnke, 2001). This observation has been experimentally demonstrated by Wondra et al. (1995b) when grinding corn with both a roller and hammermill, Healy et al. (1994) when grinding sorghum using a roller mill, and De Jong et al. (2016) when grinding wheat using a hammermill. In the current study, roller mill configuration had a significant impact on throughput. Increasing the number of grinding rolls allows the grinding action to be spread over multiple rolls, resulting in the ability to reduce particle size while still achieving greater production rates. The 4-high coarse configuration ground corn to a finer particle size than the 3-high and 2-high configurations and had a greater overall production rate. However, when the 4-high configuration was adjusted to the fine-grind settings, production rate decreased significantly as the particle size was reduced to 285 µm. Net grinding electricity consumption was lowest for the 2-high configuration as would be expected due to the coarse particle size, and reduced particle size led to a linear increase in net electricity consumption. It is important to note the challenges associated with setting appropriate roll gaps for the 3-high configuration to optimize motor load across the three sets of grinding rolls due to the configuration of drive motors and pulleys. Each motor used in the experimental roller mill powered a grinding roll on two separate roll pairs through the pulley mechanism; therefore, the 3-high configuration utilized power from four total motors, which is why net electrical consumption is reported. This method provides an accurate assessment of net power consumption for all roller mill configurations used. The lack of independent adjustment capability for each roll pair may have led to a reduced throughput and increased net electricity cost per tonne for the 3-high configuration. Such challenges would not be present with roller mills designed with only three pairs of grinding rolls. Even given the challenges associated with proper roll adjustment, the current experiment demonstrates both that roller mill configuration impacts production rate and reduced particle size targets require a greater amount of electrical power compared with coarser targets. The impact of roller mill configuration on production rate can be explained by a combination of resulting particle size and number of grinding rolls performing work.

As the number of grinding rolls is increased, the capability of the roller mill to reduce particle size of the ground material increased. Additionally, as the mean particle size is reduced, the standard deviation decreases as a result of a greater proportion of the material residing on the lower sieves shifting the distribution more towards the finest particle sizes and reducing the standard deviation. Thus, the lowest standard deviation is perhaps not an accurate measure or predictor for animal growth performance or material handling characteristics due to the decrease when distribution is shifted toward fine particle sizes without other physical analysis characteristics being considered such as particle size, flowability measures including compressibility, COD, or angle of repose, or bulk density.

An important consideration producers face when manufacturing feed is flowability of the material in the feed mill, feed handling systems, and feeder. Generally, as the particle size is reduced, the flowability of the diet is reduced (Rojas et al., 2016). Corn ground using four sets of grinding rolls (fine and coarse configurations) had the poorest flowability as indicated by COD. The 4-high fine configuration (267 and 285 µm) had the poorest angle of repose measurement. Additionally, bulk density was lowest for the 4-high fine (267 and 285 µm) configuration and greatest for the 4-high coarse (403 and 371 µm) and 2-high configurations (525 and 561 µm), with the 3-high configuration (394 and 473 µm) being intermediate. When corn ground using various roller mill configurations was manufactured into a complete swine diet, a similar trend of reduced flowability and bulk density, as well as increasing angle of repose was observed when grain was ground to a finer particle size using an increasing number of grinding rolls. Therefore, roller mill configuration can have a substantial impact on grain and diet flowability, which is driven by the particle size characteristics of the ground grain. Although there was a substantial impact of roller mill configuration on the flowability of the ground corn and complete diets, there were no instances where an intervention had to be made to manually increase or restore the flowability of the ground corn or complete diet. When grain ground to decreasing particle size is fed to nursery pigs, a characteristic reduction in intake has been observed in sorghum (Healy et al., 1994; Paulk et al., 2015) and wheat-based (Macromichalis et al., 2000) diets. More recently, as corn is ground to particle sizes of approximately 325 µm, G:F is not improved (De Jong et al., 2013, 2014b), and a reduction in ADFI is observed resulting in reduced ADG (De Jong et al., 2013). A reduction in feed intake for nursery pigs when fed diets ground to reduced particle sizes is impacted by texture and palatability of the corn fraction of the diet (Sola-Oriol et al., 2009; De Jong et al., 2014b). Bokelman et al. (2015) observed that, when given a choice, pigs consumed 80% of their ADFI from a diet manufactured with the corn fraction ground to 700 μm and 20% for the diet with corn ground to 400 μm. Currently, roller mill configuration had a significant impact on nursery pig feed preference, with a general preference for diets manufactured with corn ground using configurations achieving coarser particle sizes. When diets were offered with similar particle sizes ground using different configurations, no preference differences were observed. Nursery pigs are sensitive to diet palatability, and a predictable reduction in feed intake is commonly observed when feeding particle sizes below approximately 500 μm to nursery pigs.

Gain and efficiency responses to feeding nursery pigs with reduced particle size diets are typically inconsistent. Gain has been observed to be reduced when the corn fraction is ground to particle sizes approximately 325 μm, driven by a reduction in ADFI with no impact on G:F (De Jong et al., 2014a, 2014b). Bokelman et al. (2014) observed no significant impact of particle size on ADG or ADFI; however, an improvement in G:F was observed by reducing particle size to 400 μm from 700 μm. The improvement was not observed when diets were fed in pellet form with greatest G:F being observed from pigs fed diets manufactured with 700 μm corn fed in pelleted form. When fed to nursery pigs, diets containing corn ground to very fine mean particle sizes have an impact on feed intake with little impact on G:F, thus negatively impacting growth performance. Further reduction of particle size below 600 μm does not appear to be advantageous for nursery pig diets, even when grinding with a roller mill.

The primary reason cereal grains are ground is to increase the utilization of nutrients, and reducing the particle size has been shown to increase the utilization of energy (GE and ME) in swine diets (Healy et al., 1994; Wondra et al., 1995a, 1995b; Rojas et al., 2016). When considering finishing pig production, a relatively minor improvement in utilization of feed can result in a large economic benefit. Particle size reduction increases the surface area to volume ratio of the grain (Healy, 1994; Wondra et al., 1995c), thus allowing greater contact between grain particles and digestive enzymes. Reduction of particle size has been shown to decrease ADFI when fed to finishing pigs fed corn-based diets (Wondra et al., 1995b; De Jong et al., 2013; Nemechek et al., 2016).In the current study, feed intake was significantly impacted by roller mill configuration. However, when corn was ground to reduced particle sizes using a roller mill, an improvement in G:F was not observed, leading to a reduction in gain relative to the coarser-grinding configurations. Wondra et al. (1995b) observed a linear improvement in G:F as the mean particle size was reduced, resulting in an 8% improvement as mean particle size was reduced from 1,000 to 400 μm. De Jong et al. (2013) observed improved G:F and caloric efficiency on both a ME and NE basis when the particle size was reduced from 596 to 320 μm. Rojas et al. (2016) observed a linear improvement in G:F for gilts as particle size was reduced from 865 to 339 μm, with no impact of corn particle size on barrow G:F. However, roller mill configuration had no significant impact on overall finishing pig G:F, nor any impact on caloric efficiency on neither an ME nor NE basis. Acosta Camargo et al. (2015) observed an improvement in apparent total tract digestibility (**ATTD**) of GE in growing pigs when corn and wheat were ground from 700 to 300 μm, and in finishing pigs when the grains were ground from 700 to 500 μm. However, in finishing pigs, no further improvement in ATTD of GE was observed below 500 μm. Wondra et al. (1995b) observed a linear improvement in apparent digestibility of GE with reduced particle size to 400 μm with a similar impact on G:F. Additionally, Acosta Camargo et al. (2015) observed an improvement in ATTD of GE when using a roller mill to reduce particle size from 700 to 300 μm in corn and wheat, whereas no further improvement in ATTD of GE was observed when grinding finer than 500 μm using a hammermill. The ability of roller mills to reduce particle size in a very consistent manner without the quantity of very fine materials relative to a hammermill does not appear to consistently provide digestibility or G:F improvements below 500 μm. In the current study, roller mill configuration had a numeric impact on G:F and caloric efficiency in finishing pigs as would be consistent with previous research; however, the negative impacts of reduced ADFI lead to poorer ADG, which resulted in no advantage when grinding corn to very fine particle sizes for nursery or finishing pig diets.

In conclusion, roller mill configuration had a significant impact on milling characteristics including throughput and electricity cost, nursery pig feed preference, and finishing pig growth performance. The addition of a fourth set of grinding rolls may provide some flexibility to feed manufacturers using roller mills to grind grain; however, limitations of fine grinding (<600 μm) previously observed with hammermills, including increases in milling costs and reduced throughput and preference away from fine-ground diets with only marginal improvements in G:F, also appear to be present when using roller mills.

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