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Effects of Grinding Corn through a 2-, 3-, or 4-High Roller Mill on Milling Characteristics, and Commercial Finishing Pig Growth Performance and Carcass Characteristics

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Effects of Grinding Corn through a 2-, 3-, or 4-High Roller Mill on Milling Characteristics, and Commercial Finishing Pig Growth Performance and Carcass Characteristics[1,2]

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Summary

A total of 922 pigs [PIC TR4 × (FAST Large white × PIC Landrace), initially 88.3 lb] were used in a 97-d experiment to determine the effects of grinding corn through various roller mill configurations on milling characteristics as well as growth performance and carcass characteristics of finishing pigs in a commercial setting. Pens were randomly allotted to 1 of 4 experimental treatments by initial BW with 11 pens per treatment and 21 pigs per pen. All diets were fed in 5 phases with the same corn-soybean meal-based diets containing 20% dried distiller's grains with solubles. Experimental treatments included: (1) corn ground to 685 μm using 2 sets of rolls (2-high); (2) corn ground to 577 μm using 3 sets of rolls (3-high); (3) corn ground to 360 μm using 4 sets of rolls in a fine grind configuration (4-high fine); and (4) corn ground to 466 μm using 4 sets of rolls in a coarse grind configuration (4-high coarse). The same roller mill was used for all configurations with the appropriate lower rolls completely open when using 2 or 3 sets of rolls.

Grinding rate (tons per hour) was greatest ($P < 0.05$) for the 2-high and 4-high coarse configurations, followed by the 3-high configuration and lowest for the 4-high fine configuration. Electricity cost was lowest ($P < 0.05$) per ton of ground corn for the 2-high configuration, and was greatest for the 4-high fine configuration.

Pigs fed diets containing corn ground with the 2-high configuration had the greatest ($P < 0.05$) ADFI and ADG, and pigs fed diets with corn ground using the 4-high fine

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[2] Funding, wholly or in part, was provided by National Pork Board.

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configuration had the poorest ADFI and ADG. Pigs fed diets with corn ground using the 3-high or 4-high coarse configuration were intermediate. There were no differences ($P > 0.05$) in F/G, caloric efficiency, or carcass characteristics among pigs fed diets ground with different roller mill configurations. Feed cost/lb of gain was lowest ($P < 0.05$) for the 4-high coarse configuration and revenue/pig was greatest ($P < 0.05$) for the 2-high and 4-high coarse configurations. Income over feed cost (IOFC) was lowest ($P < 0.05$) for pigs fed diets with corn ground using the 4-high fine configuration; however, there were no differences ($P > 0.05$) in IOFC among the other milling configurations.

In our study, roller mill configuration had a significant impact on grinding electricity cost as well as grinding rate. However, when particle size was reduced from 685 µm to 360 µm, ADFI and ADG decreased, and there was no improvement in feed efficiency. Therefore, our study did not indicate a benefit in feed efficiency or economic return of finishing pigs when corn particle size was reduced below 685 µm by grinding through a roller mill in the commercial setting in this experiment.

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

Introduction

It is generally thought that as grain is ground to a finer mean particle size, a linear improvement in nutrient utilization and pig performance will be observed. Research has demonstrated this benefit when particle size is reduced from 1,000 µm to approximately 600 µm. With finishing pigs, recent research had found feed efficiency can be improved by grinding below 600 µm, but feed intake and gain also were reduced[5]. Generally, as grains are ground to a smaller mean particle size, an increasing amount of very fine particles may potentially affect the palatability of these diets and create potential flowability concerns. The two primary manufacturing processes by which corn is ground include the hammermill and roller mill. Benefits of the hammermill include the ability to handle a wide variety of ingredients and capability to grind to a very small particle size; however, the variation in the final ground grain is quite high. By comparison, the roller mill is able to grind grain to a much more consistent particle size with reduced operating costs. Previously, roller mill manufacturing technology did not allow the mean grain particle size to be reduced below 600 µm. However, more recent introduction of roller mills with 3 or 4 sets of grinding rolls allow producers to grind to a much finer particle size while minimizing the amount of very fine particles compared to a hammermill. Therefore, our objective was to compare various roller mill configurations of ground corn on milling characteristics, commercial finishing pig growth performance, and economics.

Procedures

The Kansas State University Institutional Animal Care and Use Committee approved the protocols used in these experiments. The study was conducted at New Fashion Pork commercial feedmill in Estherville, IA, and research facilities in Round Lake, MN. Research facilities were double-curtain-sided with completely slatted flooring and deep

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[5] De Jong et al., 2012. Effects of Corn Particle Size, Compete Diet Grinding, and Diet Form on Finishing Pig Growth Performance, Caloric Efficiency, Carcass Characteristics, and Economics. Swine Day 2012, Report of Progress 1074, pp. 316-324.

pits for manure storage. Pigs had approximately 7.4 ft^2/pig, and each pen was equipped with a 5-hole stainless steel dry self-feeder (Thorp Equipment, Inc., Thorp, WI) and a cup waterer for ad libitum access to feed and water. Daily feed additions to each pen were accomplished through a robotic feeding system (FeedPro, Feedlogic Corp., Willmar, MN).

A total of 922 pigs [PIC TR4 × (FAST Large white × PIC Landrace), initially 88.3 lb] were used in a 97-d experiment. Corn for treatment diets was manufactured using a roller mill with four sets of grinding rolls (RMS Roller-Grinder, Harrisburg, SD). Experimental treatments were fed in meal form and included: (1) corn ground to 685 µm using 2 sets of rolls (2-high); (2) corn ground to 577 µm using 3 sets of rolls (3-high); (3) corn ground to 360 µm using 4 sets of rolls in a fine grind configuration (4-high fine); and (4) corn ground to 466 µm using 4 sets of rolls in a coarse grind configuration (4-high coarse). The same roller mill was used for all configurations with the appropriate lower rolls completely open when using the 2 or 3 sets of rolls configurations. The roller mill configurations for each treatment were: (1) 2 sets of grinding rolls with roll gaps open to 0.035 and 0.025 in. (2-high); (2) 3 sets of grinding rolls with roll gaps open to 0.035, 0.025, and 0.020 in. (3-high); (3) 4 sets of grinding rolls with gaps open to 0.035, 0.025, 0.015, and 0.009 in. (4-high fine); and (4) 4 sets of grinding rolls with roll gaps open to 0.040, 0.030, 0.030, and 0.025 in. (4-high coarse). All grinding rolls had a 2% left spiral. The top rolls each had 6 corrugations per inch. The second (set 2) had 10 corrugations per inch while 1 roll had 12, and the 2nd roll had 14 corrugations per inch in set 3. The 4th set of rolls had 1 roll with 14 and 1 roll with 16 corrugations per inch. Thus, the number of corrugations per inch increased with each set of rolls. Roll speed was offset and was 1,126 rpm for the fast roll (16.0” diameter sheave) and 763 rpm for the slow roll (23.6” diameter sheave). Corn feed rate was set based on a targeted 85% load on the roller mill.

For the live animal portion of the experiment, pens were randomly allotted to 1 of 4 experimental treatments by initial BW with 11 pens per treatment and 21 pigs per pen, with initial BW serving as a blocking factor. All diets were the same corn-soybean meal-based diet containing 20% dried distiller’s grains with solubles (DDGS). Diets were fed in a 5-phase feeding program from 70 to 100, 100 to 140, 140 to 180, 180 to 230, and 230 to 280 lb.

Pigs were weighed, and feed disappearance was measured approximately every 2 wk to calculate ADG, ADFI, and F/G. On d 83 of the trial, pens were weighed and the 6 heaviest pigs from each pen were removed and transported 350 miles to Triumph Foods (St. Joseph, MO) for harvest. The remaining pigs were transported to Triumph Foods on d 97 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, and loin depth.

Caloric efficiencies (ME- and NE-basis) were calculated by multiplying total feed intake × energy content of the diet (kcal/lb) and dividing by total gain. A constant energy value was used for corn regardless of particle size (NRC, 2012[6]). Feed cost/pig,

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[6] NRC. 2012. Nutrient Requirements of Swine, 11th ed. Natl. Acad. Press, Washington, D.C.

feed cost/lb gain, revenue per pig, and IOFC were calculated to determine economic implications of milling treatments. Diet costs were determined using the following ingredient and processing costs: corn = \$3.75/bu, soybean meal = \$286/ton, DDGS = \$151/ton, base grind/mix/delivery fee = \$12.00/ton, supplemental grinding electricity based on roller mill configuration per ton of ground corn = 2-high (\$0.00/ton), 3-high (\$0.175/ton), 4-high fine (\$0.645/ton), 4-high coarse (\$0.246/ton). Costs were derived from collection of electricity consumption and grinding rate performance data for the roller mill, which resulted in the 2-high configuration having the lowest electricity cost/ton of ground corn. The supplemental grinding electricity cost was drawn from the additional electricity cost above the 2-high baseline cost of \$0.366/ton of ground corn, which was included in the grind/mix/delivery fee. Feed cost/pig was determined by total feed intake × diet cost (\$/lb). Feed cost/lb gain was calculated using feed cost/pig divided by total gain. Revenue/pig was determined by total gain × \$0.60/lb, and IOFC was calculated using revenue/pig – feed cost/pig. Electricity data were collected for all roller mill configurations on 23 occasions, 20 dates of experimental diet manufacturing, and 3 capacity tests to accurately determine throughput using the treatment configurations. To calculate electricity consumption for the treatments utilizing 2- and 3-sets of grinding rolls, individual roll amperage was used to calculate the amount of electricity used for grinding, and the electricity used by the extra sets of open rolls was subtracted from the electricity consumption for these configurations.

Corn ground during the capacity tests was used in manufacturing nontest diets fed within the production system. Therefore, analysis of samples fed during the growth performance portion of the experiment did not include the samples from the capacity tests. Of the 20 dates when experimental diets were manufactured, corn samples were collected and analyzed on 16 of those dates. Of those 16 dates where corn samples were collected, samples were collected from a port below the last grinding roll on 13 days. On the 3 remaining days, a sample was collected from a port beneath each set of grinding rolls for a detailed analysis of particle size reduction from each set of rolls. These samples were used for analysis of ground corn used in the experiment (Table 5). In addition, corn samples were collected between every grinding roll for the 3 capacity tests, for a total of 6 sets of samples collected between each grinding roll. Analysis of ground corn following each grinding roll (Table 6) includes the samples collected during the 3 capacity tests, as well as the 3 dates of diet manufacturing which collected samples between each grinding roll.

Complete diet samples were collected from barn within treatment at multiple locations, subsampled, and submitted for analysis of DM, CP, ADF, crude fiber, Ca, P, ether extract, ash, and starch (Ward Laboratories, Inc., Kearney, NE). Particle size analysis, bulk density, angle of repose, and flowability index were measured on all ground corn samples at the Kansas State University Swine Lab. In addition, bulk density, angle of repose, and flowability index were determined for complete diets. Flowability was measured using a Flowdex device (Hanson Research, Chatsworth, CA), which measures flowability based on an ingredient's ability to fall freely through a hole in the center of a disk. The flowability index is given as the hole diameter, expressed in millimeters, of the smallest hole disk 50 g of an ingredient falls through freely on three consecutive attempts. Additionally, flowability was measured using angle of repose in which grain was placed in a cylinder on top of an 8.7 cm diameter pedestal. The cylinder was then lifted, which allowed the excess grain to freely fall. The height of the remaining grain was measured and used to calculate angle of repose. Particle size analysis was performed on all corn samples with and without a flow agent on a 13 sieve stack and pan, using a Ro-Tap (W.S. Tyler, Mentor, OH) shaker for 15 minutes.

Data were analyzed as a randomized complete block design using PROC GLIMMIX (SAS Institute, Inc., Cary, NC) with pen as the experimental unit. Hot carcass weight was used as 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. For analysis of ground corn samples collected following each grinding roll, data were analyzed as an incomplete 4 × 4 factorial design with four roller mill configurations and four roll locations, void of one configuration × roll location combination (2-high configuration, sample following third roll). Results were considered significant at $P \leq 0.05$ and a trend at $P \leq 0.10$.

Results and Discussion

Analysis of ingredients and diets

As expected, chemical analysis of complete diets revealed no notable differences among treatments (Tables 2 to 4). Corn ground using the 2-high configuration had the greatest ($P < 0.05$) particle size, followed by a reduction in particle size for the 3-high configuration, further reduction for the 4-high coarse configuration, and the 4-high fine configuration having the finest particle size whether measured without or with a flow agent (Table 5). Particle size was 65 to 113 μm smaller when measured with a flow agent as compared to measuring without the flow agent, with the difference being greatest at the coarser particle sizes. Corn ground using the 4-high fine configuration had the lowest ($P < 0.05$) standard deviation, whereas there were no observed differences in standard deviation among the other configurations when the analysis was run without flow agent. However, when flow agent was used, the standard deviation of the 4-high fine configuration was still the lowest ($P < 0.05$) compared to all other treatments, but also the 2-high corn was greater ($P < 0.05$) than the corn from the 3-high with the 4-high course corn being intermediate. As particle size was reduced, the surface area, expressed as cm^2/gram, increased ($P < 0.05$). As expected, corn ground using the 4-high fine had the lowest bulk density, followed by the 3-high and 4-high coarse configurations, while the 2-high configuration yielded the greatest ($P < 0.05$) bulk density.

Corn ground using the 2-high configuration had the most desirable ($P < 0.05$) angle of repose flowability, followed by the 3-high and 4-high coarse configurations, and the 4-high fine configuration produced the least desirable angle of repose flowability scores. The 2-high and 3-high configurations had more desirable ($P < 0.05$) Flowdex flowability scores relative to the 4-high configurations.

As grain progresses through the roller mill, a reduction ($P < 0.05$) of particle size is observed as expected, as well as an improvement in standard deviation (Table 6). Surface area increased ($P < 0.05$) as the grain progressed through additional grinding rolls, with the exception of the 2-high configuration. Flowdex flowability index and angle of repose flowability resulted in inconsistent response as the grain progressed through the roller mill. As expected, bulk density decreased ($P < 0.05$) as the grain progressed through additional grinding rolls.

Physical analysis of diets (Table 7) for phases 1 to 5 resulted in diets manufactured with the 4-high roller mill configuration having the least desirable Flowdex flowability index as well as the least desirable angle of repose flowability score. Bulk density was greatest for the 2-high configuration and lowest for the 4-high fine configuration, as expected.

Roller mill performance

Corn ground using the 4-high fine configuration resulted in the slowest ($P < 0.05$) throughput, followed by the 3-high configuration, and the 2-high and 4-high coarse had the greatest throughput (Table 8). Corn ground using the 2-high configuration resulted in the lowest ($P < 0.05$) cost/ton of ground corn, followed by the 3-high configuration, 4-high coarse configuration, and the 4-high fine configuration resulted in the greatest cost.

Growth performance

From d 0 to 56, pigs fed diets containing corn ground with the 2-high roller mill had the greatest ($P < 0.05$) ADG, as well as increased ($P < 0.05$) ADFI compared to pigs fed diets ground using the 4-high fine configuration (Table 9). There were no differences ($P > 0.05$) in F/G among pigs fed diets from different roller mill configurations for the growth period. Additionally, from d 56 to 97, pigs fed diets containing corn ground using the 2-high configuration had the greatest ($P < 0.05$) ADG, and pigs fed diets ground using the 4-high fine configuration had the poorest ($P < 0.05$) ADFI. Pigs fed diets ground using the 2-high roller mill configuration had poorer ($P < 0.05$) F/G compared to pigs fed diets ground using the 4-high coarse configuration.

Overall (d 0 to 97), pigs fed diets containing corn ground with the 2-high roller mill and the 4-high coarse configuration had the greatest ADG ($P < 0.05$), compared to pigs fed diets with corn ground using the 4-high fine configuration. Pigs fed diets ground using the 4-high fine configuration had the lowest ($P < 0.05$) ADFI; however, there were no differences ($P > 0.05$) in F/G or caloric efficiency among roller mill configurations. Pigs fed diets containing corn manufactured with the 2-high configuration had greater ($P < 0.05$) final BW and HCW than pigs fed diets containing corn manufactured with the 4-high fine configuration. There were no differences ($P > 0.05$) in carcass yield, backfat, loin depth, or percentage lean among roller mill configurations.

Economic analysis

The economic analysis showed that feed cost/pig was greatest ($P < 0.05$) for pigs fed diets containing corn ground using the 2-high configuration, whereas pigs fed diets with corn ground with the 4-high configurations had the lowest feed cost/pig. Feed cost/lb gain was lowest ($P < 0.05$) for the 4-high coarse configuration and revenue/pig was greatest for the 2-high and lowest for the 4-high fine configuration. IOFC was least ($P < 0.05$) for pigs fed diets ground using the 4-high fine configuration; however, there were no differences ($P > 0.05$) in IOFC among the other configurations.

In conclusion, our study indicated a significant impact of roller mill configuration on grinding electricity cost as well as throughput. Grinding to a particle size of 360 μm resulted in a substantial decrease in feed intake as well as growth rate; however, a feed efficiency improvement was not observed relative to the other roller mill configurations. Palatability of diets containing corn ground to less than 600 μm appears to be a concern when the diets are fed in meal form. Recent advances in roller mill technology allow producers to achieve a finer mean particle size than was previously available with roller mills; however, this study indicates particle size reduction below 685 μm with a roller mill did not improve economic return.

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

	Dietary phase				
Item	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Ingredient, %					
Corn	57.81	62.02	65.68	69.05	70.99
Soybean meal	19.41	15.52	12.08	8.66	6.91
DDGS[2]	20.00	20.00	20.00	20.00	20.00
Dicalcium phosphate	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-lysine HCl	0.45	0.43	0.40	0.40	0.35
L-threonine	0.08	0.06	0.04	0.05	0.04
L-tryptophan	0.03	0.03	0.02	0.03	0.02
MHA dry (Methionine)	0.08	0.05	0.03	0.02	- - -
Vitamin and mineral premix[3]	0.15	0.15	0.15	0.15	0.15
Total	100	100	100	100	100

continued

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

	Dietary phase				
Item	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Calculated analysis[4]					
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/lb	1,456	1,462	1,466	1,467	1,469
NE, kcal/lb	1,117	1,130	1,141	1,149	1,155
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
Available P, %	0.40	0.36	0.33	0.30	0.30

[1] Treatment diets were fed to 922 pigs [PIC TR4 × (FAST Large white × PIC Landrace), initially 88.3 lb] for a 97-d growth experiment in a 5-phase feeding program formulated to 70 to 100, 100 to 140, 140 to 180, 180 to 230, and 230 to 280 lb BW ranges.

[2] DDGS = dried distillers grains with solubles.

[3] VTM premix provided an estimated release of 0.12% available P.

[4] NRC. 2012. Nutrient Requirements of Swine, 11th ed. Natl. Acad. Press, Washington, D.C.

Table 2. Chemical analysis of diets, Phases 1 and 2 (as-fed basis)[1]

	Phase 1				Phase 2			
	Roller mill configuration[2]				Roller mill configuration[2]			
Item	2-high	3-high	4-high fine	4-high coarse	2-high	3-high	4-high fine	4-high coarse
DM, %	88.91	88.98	88.48	88.59	87.87	88.19	87.63	87.88
CP, %	18.7	19.6	18.1	19.0	15.6	15.4	16.6	15.7
ADF, %	5.5	6.4	6.1	5.8	5.2	5.4	5.7	5.4
Ca, %	0.79	0.62	0.60	0.76	0.64	0.63	0.70	0.56
P, %	0.51	0.48	0.49	0.5	0.44	0.43	0.44	0.44
Ether extract, %	3.4	3.4	3.6	3.2	3.3	3.4	3.3	3.4
Ash, %	4.6	4.1	4.2	4.3	4.0	3.7	4.0	3.5
Starch, %	34.1	33.9	35.7	37.2	43.1	41.9	41.4	39.7

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

[2] Corn was ground using 2 sets of rolls (685 µm), 3 sets of rolls (577 µm), 4 sets of rolls in a fine-grind configuration (360 µm), or 4 sets of rolls in a coarse configuration (466 µm) fed in a 5-phase feeding program formulated to 70 to 100, 100 to 140, 140 to 180, 180 to 230, and 230 to 280 lb BW ranges.

Table 3. Chemical analysis of diets, Phases 3 and 4 (as-fed basis)[1]

	Phase 3				Phase 4			
	Roller mill configuration[2]				Roller mill configuration[2]			
Item	2-high	2-high	4-high fine	4-high coarse	2-high	3-high	4-high fine	4-high coarse
DM, %	88.02	88.01	87.95	88.1	88.64	89.54	88.36	88.33
CP, %	15.9	15.7	16.4	16.6	14.9	14.0	13.5	14.5
ADF, %	5.8	4.7	5.7	6.0	3.7	3.1	4.1	3.8
Ca, %	0.71	0.54	0.56	0.57	0.59	0.48	0.51	0.50
P, %	0.43	0.45	0.44	0.44	0.43	0.41	0.41	0.41
Ether extract, %	3.1	3.1	3.2	3.4	4.1	3.4	3.6	3.7
Ash, %	3.8	3.6	3.6	3.3	3.6	3.2	3.3	3.3
Starch, %	43.9	40.9	39.9	39.9	40.4	40.0	41.2	42.5

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

[2] Corn was ground using 2 sets of rolls (685 µm), 3 sets of rolls (577 µm), 4 sets of rolls in a fine-grind configuration (360 µm), or 4 sets of rolls in a coarse configuration (466 µm) fed in a 5-phase feeding program formulated to 70 to 100, 100 to 140, 140 to 180, 180 to 230, and 230 to 280 lb BW ranges.

Table 4. Chemical analysis of diets, Phase 5 (as-fed basis)[1]

	Phase 5			
	Roller mill configuration[2]			
Item	2-high	2-high	4-high fine	4-high coarse
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 was collected from feeders within treatment and phase, subsampled, and submitted to Ward Laboratories (Kearney, NE) for analysis.

[2] Corn was ground using 2 sets of rolls (685 µm), 3 sets of rolls (577 µm), 4 sets of rolls in a fine-grind configuration (360 µm), or 4 sets of rolls in a coarse configuration (466 µm) fed in a 5-phase feeding program formulated to 70 to 100, 100 to 140, 140 to 180, 180 to 230, and 230 to 280 lb BW ranges.

Table 5. Physical analysis of ground corn used in growth trial[1]

	Roller mill configuration[2]					
Item	2-high	3-high	4-high fine	4-high coarse	SEM	Probability, $P <$
Without flow agent						
Particle size, µm[3]	685^{a}	577^{b}	360^{d}	466^{c}	16.8	0.001
St. dev.	2.32^{a}	2.28^{a}	2.09^{b}	2.31^{a}	0.043	0.001
Surface area[4,5]	94.3^{d}	111.2^{c}	169.0^{a}	140.6^{b}	4.64	0.001
With flow agent[6]						
Particle size, µm[3]	572^{a}	484^{b}	295^{d}	382^{c}	16.5	0.001
St. dev.	3.02^{a}	2.94^{b}	2.55^{c}	2.95^{a,b}	0.064	0.001
Surface area[4,5]	144.1^{d}	168.2^{c}	240.2^{a}	216.3^{b}	10.74	0.001
Flowdex, mm[7]	22.6^{b}	22.7^{b}	25.0^{a}	25.2^{a}	0.97	0.001
Angle of repose	47.8^{c}	50.1^{b}	54.7^{a}	53.8^{a}	0.38	0.001
Bulk density, lb/bu[8]	40.4^{a}	39.6^{b}	37.5^{c}	39.7^{b}	0.62	0.001

[1] Analysis included only samples of ground grain that were fed during the growth trial and collected at the bottom of the roller mill (16 samples per treatment).

[2] Corn was ground using 2 sets of rolls (685 µm), 3 sets of rolls (577 µm), 4 sets of rolls in a fine-grind configuration (360 µm), or 4 sets of rolls in a coarse configuration (466 µm).

[3] Particle size was determined using a Ro-Tap Shaker (W.S. Tyler, Mentor, OH) with 13 sieves and a pan with a shake time of 15 minutes, using either flow agent or no flow agent.

[4] Expressed in cm^2/g.

[5] Surface area is calculated by: (6 / specific weight) ^ ((0.5 × natural log (standard deviation)^2) – (natural log (particle size × 0.0001))).

[6] 0.50 grams amorphous silica powder (Gilson Company, Inc., Lewis Center, OH) added as sieving agent to 100.0 gram grain sample.

[7] Flowdex (Hanson Research, Chatsworth, CA) flowability index represents smallest diameter disk in which 50 grams of material flows on three consecutive attempts.

[8] Bulk density was calculated in g/qt then converted to lb/bu.

[a,b,c] Means with unlike superscripts differ ($P < 0.05$).

Table 6. Characterization of roller mill ground corn[1,2]

	Roller mill configuration[3]				
Item	2-high[4]	3-high	4-high fine	4-high coarse	SEM
Without flow agent					
Particle size, µm[5]					
Roll 1	$874^{a,b}$	$900^{a,b}$	845^{b}	948^{a}	30.5
Roll 2	657^{c}	635^{c}	626^{c}	668^{c}	30.5
Roll 3	- - -	$506^{d,e}$	$433^{e,f}$	539^{d}	30.5
Bottom	695^{c}	543^{d}	364^{f}	$509^{d,e}$	30.5
St. dev.					
Roll 1	2.83^{b}	2.83^{b}	2.94^{a}	$2.84^{a,b}$	0.057
Roll 2	$2.35^{d,e}$	$2.44^{c,d}$	2.46^{c}	2.49^{c}	0.057
Roll 3	- - -	$2.35^{d,e}$	$2.35^{d,e}$	2.48^{c}	0.057
Bottom	2.33^{e}	$2.23^{f,g}$	2.14^{g}	$2.29^{e,f}$	0.057
Surface area[6,7]					
Roll 1	$90.3^{g,h,i}$	$87.9^{h,i}$	$97.5^{e,f,g,h,i}$	83.5^{i}	5.97
Roll 2	$101.2^{e,f,g,h}$	$107.2^{d,e,f}$	$109.7^{d,e}$	$104.3^{d,e,f,g}$	5.97
Roll 3	- - -	131.4^{c}	152.5^{b}	127.7^{c}	5.97
Bottom	$94.8^{f,g,h,i}$	$119.1^{c,d}$	168.7^{a}	126.2^{c}	5.97
With flow agent[8]					
Particle size, µm[5]					
Roll 1	658^{b}	$717^{a,b}$	660^{b}	742^{a}	26.2
Roll 2	$519^{c,d,e}$	$496^{d,e,f}$	$502^{d,e}$	$544^{c,d}$	26.2
Roll 3	- - -	$398^{g,h}$	$338^{h,i}$	$426^{f,g}$	26.2
Bottom	575^{c}	$460^{e,f,g}$	296^{i}	417^{g}	26.2
St. dev.					
Roll 1	4.01^{a}	4.02^{a}	4.15^{a}	4.08^{a}	0.088
Roll 2	$3.18^{c,d}$	$3.30^{b,c}$	$3.33^{b,c}$	3.37^{b}	0.088
Roll 3	- - -	3.09^{d}	$3.05^{d,e}$	$3.27^{b,c}$	0.088
Bottom	$3.05^{d,e}$	2.84^{f}	2.62^{g}	$2.93^{e,f}$	0.088
Surface area[6,7]					
Roll 1	$183.8^{d,e}$	$168.1^{e,f}$	$193.2^{c,d,e}$	$167.9^{e,f}$	11.15
Roll 2	$173.8^{d,e,f}$	$189.1^{d,e}$	$189.1^{d,e}$	$176.9^{d,e}$	11.15
Roll 3	- - -	$217.7^{b,c}$	251.9^{a}	$216.3^{b,c}$	11.15
Bottom	150.0^{f}	$179.2^{d,e}$	$236.7^{a,b}$	$196.1^{c,d}$	11.15
Flowdex index, mm[9,10]					
Roll 1	26.5	25.5	26.8	26.5	0.92
Roll 2	22.8	24.1	23.1	24.5	0.92
Roll 3	- - -	23.8	26.1	25.1	0.92
Bottom	22.5	21.5	24.5	24.8	0.92

continued

Table 6. Characterization of roller mill ground corn[1,2]

	Roller mill configuration[3]				
Item	2-high[4]	3-high	4-high fine	4-high coarse	SEM
Angle of repose					
Roll 1	47.8^{f}	$48.5^{d,e,f}$	$48.6^{d,e,f}$	$48.2^{e,f}$	0.69
Roll 2	$48.5^{d,e,f}$	$49.9^{d,e}$	$49.0^{d,e,f}$	50.2^{d}	0.69
Roll 3	- - -	54.4^{c}	$54.8^{a,b}$	$53.1^{b,c}$	0.69
Bottom	$48.6^{d,e,f}$	50.3^{d}	55.3^{a}	$53.4^{a,b,c}$	0.69
Bulk density, lb/bu[11]					
Roll 1	42.3^{a}	42.4^{a}	42.3^{a}	42.6^{a}	0.54
Roll 2	40.5^{b}	40.5^{b}	40.4^{b}	40.6^{b}	0.54
Roll 3	- - -	$39.3^{c,d}$	39.0^{d}	40.2^{b}	0.54
Bottom	$39.9^{b,c}$	38.9^{d}	37.4^{e}	$39.3^{c,d}$	0.54

[1] Roller mill configuration × roll location interactive means within response criteria with different superscripts within rows or columns differ ($P < 0.05$).

[2] Analysis included only samples collected on dates of manufacture that collected samples below each grinding roll (6 samples per treatment).

[3] Corn was ground using 2 sets of rolls (685 µm), 3 sets of rolls (577 µm), 4 sets of rolls in a fine-grind configuration (360 µm), or 4 sets of rolls in a coarse configuration (466 µm).

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

[5] Particle size was determined using a Ro-Tap Shaker (W.S. Tyler, Mentor, OH) with 13 sieves and a pan with a shake time of 15 minutes, using either flow agent or no flow agent.

[6] Expressed in cm^2/g.

[7] Surface area is calculated by: (6 / specific weight) ^ ((0.5 × natural log (standard deviation)^2) - (natural log (particle size × 0.0001))).

[8] 0.50 grams amorphous silica powder (Gilson Company, Inc., Lewis Center, OH) added as sieving agent to 100.0 gram grain sample.

[9] Flowdex (Hanson Research, Chatsworth, CA) flowability index represents smallest diameter disk in which 50 grams of material flows on three consecutive attempts.

[10] Roller mill configuration × roll location interaction for Flowdex flowability ($P > 0.05$).

[11] Bulk density was calculated in g/qt then converted to lb/bu.

Table 7. Physical analysis of diets[1]

	Roller mill configuration[2]			
Item	2-high	3-high	4-high fine	4-high coarse
Phase 1				
Flowdex, mm[3]	20.0	20.0	26.0	24.0
Angle of repose	48.6	49.4	50.3	50.5
Bulk density, lb/bu[4]	43.9	43.6	43.3	43.9
Phase 2				
Flowdex, mm[3]	26.0	28.0	30.0	26.0
Angle of repose	53.1	54.7	56.4	52.8
Bulk density, lb/bu[4]	42.5	41.2	41.6	41.9
Phase 3				
Flowdex, mm[3]	28.0	28.0	28.0	26.0
Angle of repose	52.7	56.4	57.0	53.5
Bulk density, lb/bu[4]	41.8	41.2	41.1	41.6
Phase 4				
Flowdex, mm[3]	22.0	22.0	28.0	26.0
Angle of repose	46.8	49.5	53.9	53.5
Bulk density, lb/bu[4]	41.8	40.9	40.0	40.3
Phase 5				
Flowdex, mm[3]	28.0	24.0	30.0	28.0
Angle of repose	51.8	52.0	54.8	53.3
Bulk density, lb/bu[4]	40.3	40.8	39.2	40.5

[1] A composite sample collected from feeders within treatment was used for analysis.

[2] Corn was ground using 2 sets of rolls (685 μm), 3 sets of rolls (577 μm), 4 sets of rolls in a fine-grind configuration (360 μm), or 4 sets of rolls in a coarse configuration (466 μm) fed in a 5-phase feeding program formulated to 70 to 100, 100 to 140, 140 to 180, 180 to 230, and 230 to 280 lb BW ranges.

[3] Flowdex (Hanson Research, Chatsworth, CA) flowability index represents smallest diameter disk in which 50 grams of material flows on three consecutive attempts.

[4] Bulk density was calculated in g/qt then converted to lb/bu.

Table 8. Roller mill electricity consumption[1]

	Roller mill configuration[2]					
Item	2-high	3-high	4-high fine	4-high coarse	SEM	Probability, $P <$
Grinding rate, ton/hr[3]	13.39^a	12.07^b	8.24^c	14.46^a	0.4486	0.001
Electricity cost, \$/ton[4]	0.366^d	0.541^c	1.011^a	0.612^b	0.0321	0.001

[1] Collection of data occurred on 23 dates (20 diet manufacture dates, 3 capacity tests).

[2] Corn was ground using 2 sets of rolls (685 μm), 3 sets of rolls (577 μm), 4 sets of rolls in a fine-grind configuration (360 μm), or 4 sets of rolls in a coarse configuration (466 μm).

[3] Grinding rate = tons corn ground/hour.

[4] Electricity cost = \$/ton ground corn. Cost of electricity was fixed at \$0.13/kWh.

[a,b,c] Means with unlike superscripts differ ($P < 0.05$).

Table 9. Effects of roller mill configuration on growth performance of finishing pigs[1]

	Roller mill configuration[2]					
Item	2-high	3-high	4-high fine	4-high coarse	SEM	Probability, *P* <
BW, lb						
d 0	88.3	88.3	88.3	88.3	0.78	1.000
d 56	214.6[a]	210.9[b]	209.4[b]	210.9[b]	1.13	0.004
d 97	291.7[a]	287.2[a,b]	282.1[b]	287.4[a,b]	2.06	0.022
d 0 to 56						
ADG, lb	2.22[a]	2.18[b]	2.14[b]	2.18[b]	0.014	0.005
ADFI, lb	5.59[a]	5.49[a]	5.37[b]	5.47[a,b]	0.042	0.008
F/G	2.51	2.52	2.50	2.51	0.015	0.770
d 56 to 97						
ADG, lb	2.10[a]	2.06[a]	1.96[b]	2.08[a]	0.028	0.006
ADFI, lb	7.15[a]	6.86[b]	6.57[c]	6.85[b]	0.077	0.001
F/G	3.40[a]	3.33[a,b]	3.35[a,b]	3.30[b]	0.026	0.074
d 0 to 97						
ADG, lb	2.18[a]	2.13[b]	2.07[c]	2.14[a,b]	0.014	0.001
ADFI, lb	6.20[a]	6.03[b]	5.83[c]	6.02[b]	0.047	0.001
F/G	2.85	2.83	2.82	2.81	0.013	0.147
Caloric efficiency[3]						
ME	4,176	4,144	4,125	4,120	19.6	0.145
NE	3,257	3,232	3,217	3,214	15.3	0.136

continued

Table 9. Effects of roller mill configuration on growth performance of finishing pigs[1]

	Roller mill configuration[2]					
Item	2-high	3-high	4-high fine	4-high coarse	SEM	Probability, *P* <
Carcass characteristics[4]						
HCW, lb	210.5^{a}	207.8^{a,b}	204.4^{b}	207.0^{a,b}	1.39	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	60.29	59.5	0.88	0.559
Lean, %[5]	52.41	52.20	52.64	52.22	0.256	0.472
Economics[6,7]						
Feed cost/pig, $	55.68^{a}	54.02^{b}	52.39^{c}	52.85^{b,c}	0.417	0.001
Feed cost/lb gain, $[8]	0.264^{a}	0.261^{a}	0.261^{a}	0.255^{b}	0.0012	0.001
Revenue/pig, $[9]	126.66^{a}	124.08^{b}	120.62^{c}	124.55^{a,b}	0.842	0.001
IOFC, $[10]	70.99^{a}	70.06^{a}	68.23^{b}	71.70^{a}	0.571	0.001

[1] A total of 922 finisher pigs (initially 88.3 lb) were used with 21 pigs per pen and 11 replications per treatment.

[2] Corn was ground using 2 sets of rolls (685 μm), 3 sets of rolls (577 μm), 4 sets of rolls in a fine-grind configuration (360 μm), or 4 sets of rolls in a coarse configuration (466 μm).

[3] Caloric efficiency is expressed as kcal/lb gain, using energy values for ME and NE from NRC (2012) Nutrient Requirements of Swine, 11th ed. Natl. Acad. Press, Washington, D.C.

[4] The largest 6 pigs were marketed from each pen on d 83. All remaining pigs were marketed from each pen on d 97. Carcass characteristics other than yield were adjusted by using HCW as a covariate.

[5] Calculated using NPPC (1991) guidelines for lean containing 5% fat. Lean % = (2.83 + (0.469 × (HCW)) – (18.47 × (fat depth)) + (9.824 × loin depth)) / (HCW).

[6] Major ingredient prices: corn = $3.75/bu, soybean meal = $286/ton, DDGS = $151/ton.

[7] Diet cost=Base diet cost per phase + (amount of corn/ton) × additional electricity cost above base. Electricity costs by treatment, 2 - high = $0.37/ton ground corn, 3 - high = $0.54, 4 – high fine = $1.01, 4 – high coarse = $0.61.

[8] Feed cost/lb gain = (feed cost/pig)/total gain.

[9] Total revenue/pig = total gain/pig × $0.60.

[10] Income over feed cost = total revenue/pig – feed cost/pig.

[a,b,c] Means with unlike superscripts differ ($P < 0.05$).