Title: **Should Producers Invest in 2-High, 3-High, or 4-High Roller Mills? -NPB project #14-068**

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Institution: Kansas State University

Date Submitted: July 31, 2015

Revised

Industry Summary:

The overall objective of this research is to help producers decide whether they should invest in a 2-High, 3-High, or 4-High roller mill when considering technology to reduce particle size to maximize performance of nursery pigs, finishing pigs, as well as feedmill efficiency. In order to accomplish the overall objective, three experiments were conducted to evaluate the effects of various roller mill configurations on feed preference of nursery pigs, growth performance of nursery and finishing pigs, carcass characteristics of finishing pigs, and feedmill throughput and economic implications. In Exp. 1, diets were fed with the corn fraction ground using two, three, or four sets of grinding rolls in various configurations to determine growth performance of nursery pigs. In Exp. 2, diets were fed with the corn fraction ground using the same roller mill configurations to Exp. 1 to determine feed preference in nursery pigs. In Exp. 3, diets were fed to finishing pigs with the corn fraction ground using identical roller mill configurations to determine growth performance, carcass characteristics, and throughput and electricity consumption of the roller mill.

In nursery pigs, there were no observed differences in gain, feed consumption, feed efficiency, or economics for the roller mill configurations. However, there was a clear impact of roller mill configuration on feed preference, due to the particle size of the respective diets. In finishing pigs, ADFI and ADG were reduced when the particle size was reduced from 685 μ to 360 μ, with no observed improvement in feed efficiency. Although roller mill configuration had a substantial impact on the electricity cost and throughput, results did not indicate any benefit in feed efficiency or economic return when particle size was reduced below 685 μ by grinding through a roller mill when fed to finishing pigs.

Producer bottom line;

- Earlier research has shown a decrease in gain and feed intake when corn particle size is reduced below approximately 600 μ and fed in meal diets; however, the appreciable benefit in feed efficiency normally found with particle size reduction was not observed in these studies.
- Lowering particle size by increasing the number of grinding rolls increased electricity cost and decreased throughput.
- No benefit in performance or economics was observed when corn particle size was reduced below 650 μ and fed in meal diets to nursery or finishing pigs.
- Field experience indicates that a 3-high roller mill allows producers to more easily reach their particle size targets; however, these trials indicate no advantage to use of a 4-high roller mill.

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

Scientific Abstract:

A total of 1,332 pigs were used in three studies to determine the effects of various roller mill configurations on performance and feed preference of nursery pigs, growth and carcass performance of finishing pigs, electricity consumption, roller mill throughput, and economic implications.

In Exp. 1, pens of pigs (320 DNA 400 × 200, initial BW 24 lb) were randomly allotted to 1 of 4 dietary treatments and fed for 21 d with 16 pens per treatment and 5 pigs per pen. The 4 dietary treatments used the identical corn-soybean meal-based formulation that were batched from the same batch of ingredients (Table 1). Experimental diets were: (1) feed with corn fraction ground to 650 μ using 2 sets of rolls (2-High); (2) feed with corn fraction ground to 495 μ using 3 sets of rolls (3-High); (3) feed with corn fraction ground to 340 μ using 4 sets of rolls in a fine grind configuration (4-High fine); and (4) feed with the corn fraction ground to 490 μ 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. There were no differences ($P > 0.05$) in ADG, ADFI or F/G between roller mill configurations. Similarly, no differences were observed ($P > 0.05$) for caloric efficiency or economics among roller mill configurations.

In Exp. 2, 90 pigs (PIC 327 × 200; initial BW 27 lb) were randomly allotted to one of three diet comparisons to determine feed preference. The 3 diets used were from the 2-high roller mill configuration or the fine or coarse 4 high roller mill ground corn. Each pen contained 2 feeders, each containing 1 of the 3 treatment diets. The 3 diet comparisons tested were 2-High vs. 4-High fine (1 vs. 3), 2-High vs. 4-High coarse (1 vs. 4), and 4-High Fine vs. 4-High Coarse (3 vs. 4). Feeders were rotated once daily within each pen for the 7-d study. There were 5 pigs per pen, and 6 pens per treatment. Pigs consumed 67% ($P < 0.05$) of the diet containing corn ground through the 2-High roller mill compared to only 33% from the diet containing 4-High fine corn (Table 6). There was no difference ($P > 0.05$) in feed consumption of 2-High roller mill manufactured diet and diet manufactured with the 4-High roller mill in a coarse configuration (50.3 to 49.7%, respectively). However pigs consumed 63% ($P < 0.05$) of the diet manufactured using the 4-High roller mill in a coarse configuration and only 37% from the diet using the 4-High mill in a fine grind configuration.

In Exp. 3, 922 pigs (PIC TR4 × (FAST Large white × PIC Landrace), initial BW 88.3 lb) were used in a 97-d experiment to determine the effects of grinding corn through various roller mill configurations on growth performance and electrical consumption. 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 five phases with the same corn-soybean meal-based diets containing 20% dried distiller's grains with solubles. The treatments were the same as Exp. 1 with: (1) corn ground to 685 μ using 2 sets of rolls (2-High); (2) corn ground to 577 μ using 3 sets of rolls (3-High); (3) corn ground to 360 μ using 4 sets of rolls in a fine grind configuration (4-High fine); and (4) corn ground to 466 μ using 4 sets of rolls in a coarse grind configuration (4-High coarse).

Pigs fed diets containing corn ground with the 2-High configurations had the greatest ($P < 0.05$) ADFI and ADG with pigs fed diets with corn ground using the 4-High fine configuration having the poorest ADFI and ADG. Pigs fed diets ground using the 3-High or 4-High coarse configuration had intermediate ADFI and ADG. There were no observed differences ($P > 0.05$) in F/G or caloric efficiency among roller mill configurations. There also were no observed differences ($P > 0.05$) in yield, backfat, loin depth, or percent lean among roller mill configurations. Feed cost/pig matched feed intake being greatest 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 ($P < 0.05$) 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 4-High coarse configurations. IOFC was lowest ($P < 0.05$) for pigs fed diets with corn ground using the 4-High fine configuration; however, there were no observed differences ($P > 0.05$) in IOFC among the other configurations.

Grinding rate was significantly impacted by roller mill configuration, with the 4-High fine configuration having the lowest ($P < 0.05$) throughput. Grinding rate was greatest ($P < 0.05$) for the 2-High and 4-High coarse configurations, followed by the 3-High 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.

In nursery pigs, there were no observed differences in gain, feed consumption, feed efficiency, or economics for the roller mill configurations. However, there was a clear impact of roller mill configuration on feed preference with preference being negatively impacted by fine particle sizes. In finishing pigs, ADFI and ADG was reduced when the particle size was reduced from 685 μ to 360 μ, with no observed improvement in feed efficiency. Results did not indicate any benefit in feed efficiency or economic return when particle size was reduced below 685 μ by grinding through a roller mill when fed to finishing pigs.

Introduction:

It is generally thought that as diets are ground to a smaller 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 microns to approximately 600 microns. However, further reduction of particle size below 600 microns has not shown benefits when fed to nursery pigs when the grain is ground using a hammer mill. Research with finishing pigs found feed intake and gain was reduced when pigs were fed diets containing corn ground below 600 microns. Generally, as grains are ground to a small mean particle size, there becomes an increasing amount of very fine particles that may potentially affect the palatability of these diets. The two primary manufacturing processes by which corn is ground include the hammer mill and roller mill. Benefits of the hammer mill 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 compared to a hammer mill. Previously, roller mill manufacturing technology did not allow the mean particle size to be reduced as fine as a hammer mill. However, recent advances in feed manufacturing technology allow producers to grind to a much finer particle size using three or four sets of grinding rolls, while maintaining a consistent mean particle size and minimizing the amount of very fine particles compared to a hammer mill.

Therefore, the objective of this series of experiments was to compare various roller mill configurations on feed preference and performance of nursery pigs, growth performance, electrical consumption, and economics when fed to finishing pigs, and roller mill electricity consumption and throughput.

Objectives:

The overall objective was to help producers decide whether they should invest in a 2-high, 3-high, or 4-high roller mill when considering technology to reduce particle size. In order to achieve this overall objective, the specific objectives were to:

1) Determine the influence of corn ground as fine as possible through a 2-high, 3-high, or 4-high roller mill on nursery and finishing pig performance.
2) Determine if the reduced standard deviation of mean particle of corn ground through a 4-high roller mill will be advantageous to corn ground to the same mean particle size via 2-high roller mill.
3) Determine if different mean corn particle size and variation of particle size effects pig's preference to consume feed.
4) Determine the economic return to using a 2-high, 3-high, or 4-high roller mill.

Materials & Methods:

Three separate experiments were conducted to answer our objectives. All three trials used identical roller mill configurations which included (1) corn ground using 2 sets of rolls (2-High); (2) corn ground using 3 sets of rolls (3-High); (3) corn ground using 4 sets of rolls in a fine grind configuration (4-High fine); and (4) corn ground using 4 sets of rolls in a coarse grind configuration (4-High coarse).

The Kansas State University Institutional Animal Care and Use Committee approved the protocols used in these experiments. Exp. 1 and 2 were conducted at the K-State Swine Teaching and Research Center and Segregated Early Weaning Facility in Manhattan, KS in which a total of 410 pigs were used in two experiments. In both experiments, pigs were randomly allotted to pens based on initial pig weight following weaning and were fed a common diet until reaching approximately 25 lb. All corn used in experimental diets was ground at New Fashion Pork's commercial feedmill located in Estherville, Iowa using a 4-High roller mill (RMS Roller-Grinder, Harrisburg, SD) and subsequently transported to the O.H. Kruse feedmill at Kansas State University for manufacture of the complete diets. Exp. 3 was conducted at New Fashion Pork commercial feedmill located in Estherville, IA and research facilities in Round Lake, MN. Research facilities were double-curtain-sided with completely slatted flooring and deep 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).

Exp. 1 and 2

In Exp. 1, pens of pigs (320 DNA 400 × 200, initial BW 24 lb) were randomly allotted to 1 of 4 dietary treatments and fed for 21 d with 16 pens per treatment and 5 pigs per pen. The 4 dietary treatments used the identical corn-soybean meal-based formulation that were batched from the same batch of ingredients (Table 1). Experimental diets were: (1) feed with corn fraction ground to 650 μ using 2 sets of rolls; (2) feed with corn fraction ground to 495 μ using 3 sets of rolls; (3) feed with corn fraction ground to 340 μ using 4 sets of rolls in a fine grind configuration; and (4) feed with the corn fraction ground to 490 μ using 4 sets of rolls in a coarse grind configuration. Pig weights and feed disappearance were measured on d 0, 7, 14, and 21 to determine ADG, ADFI, and F/G.

Caloric feed efficiency was determined on both an ME and NE basis (NRC, 2012) and calculated by multiplying total feed intake × energy content of the diet (kcal/lb) and dividing by total gain. Feed cost/pig, feed cost/lb gain, revenue per pig, and IOFC were calculated to determine economic implications. Diet costs were determined using the following ingredient and processing costs: corn = $3.75/bu, soybean meal = $286/ton, base grind/mix/delivery fee = $12.00/ton, supplemental grinding electricity based on roller mill configuration = 2-High ($0.00/ton corn), 3-High ($0.175/ton corn), 4-High fine ($0.645/ton corn), 4-High coarse ($0.246/ton corn). 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 ground corn. The supplemental grinding electricity cost was drawn from the average additional electricity cost above the 2-High baseline cost of $0.3663/ton ground corn, which was included in the grind/mix/delivery fee. Feed cost/pig was determined by total feed intake × diet cost ($/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 live gain, and IOFC was calculated using revenue/pig – feed cost/pig.

In Exp. 2, 90 pigs (PIC 327 × 1050, initial BW 27 lb) were randomly allotted to 1 of 3 dietary treatments with 6 pens per treatment and 5 pigs per pen. Experimental diets were fed for 7 d. Diets from treatments 1, 3, and 4 from Exp. 1 were used to determine the effect of grinding on feed preference. Each pen contained either two, 2-hole, dry self-feeders or two, 4-hole, dry self-feeders balanced among comparisons as well as a nipple waterer to provide ad libitum access to feed and water. Thus, the preference between 2 of the 3 diets could be tested within each pen. Feeders were rotated daily within each pen for the 7-d study. The 3 diet comparisons tested were 2-High vs. 4-High fine (1 vs. 3), 2-High vs. 4-High coarse (1 vs. 4), and 4-High fine vs. 4-High coarse (3 vs. 4). Pens had wire-mesh floors and allowed approximately 3.6 ft^2/pig. Feeders were weighed on d 0, 2, 4, and 7, and pig weights were collected on d 0 and 7 of the trial to determine ADG, ADFI, and F/G.

Exp. 3

A total of 922 pigs (PIC TR4 × (FAST Large white × PIC Landrace), initial BW 88.3 lb) were used in a 97-d experiment to determine the effects of grinding corn through various roller mill configurations on growth performance and electrical consumption. Corn for treatment diets was manufactured using a roller mill with four sets of grinding rolls (RMS Roller-Grinder, Harrisburg, SD). All diets were fed in meal form. Electrical consumption data was collected during manufacture of treatment diets, as well as during a set of three capacity tests to accurately determine throughput over a three hour period. Ground corn samples were collected as material exited the roller mill, as well as between every grinding roll periodically throughout the trial to characterize the corn as it progressed through additional grinding rolls. To calculate electricity consumption for the treatments utilizing two and three sets of grinding rolls, individual roll amperage was used to calculate the amount of electricity used to perform the grinding process, and the electricity used by the extra sets of open rolls was subtracted from the electricity consumption for these configurations. Roller mill treatment configurations were: (1) two sets of grinding rolls with roll gaps configured 0.035”, 0.025”, open, open; (2) three sets of grinding rolls configured 0.035”, 0.025”, 0.020”, open; (3) four sets of grinding rolls configured 0.035”, 0.025”, 0.015”, 0.009” (4-High fine); and (4) four sets of grinding rolls configured 0.040”, 0.030”, 0.030”, 0.025” (4-High coarse). Grinding rolls had a 2% left spiral, with rolls in roll set 1 each having 6 corrugations per inch, rolls in roll set 2 each had 10 corrugations per inch, rolls 1 and 2 in set 3 had 12 and 14 corrugations per inch, respectively, and rolls 1 and 2 in roll set 4 had 14 and 16 corrugations per inch, respectively. Roll speed was set at 1126 rpm for the fast roll (16.0” diameter sheave) and 763 rpm for the slow roll (23.6” diameter sheave). Feeder 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 weight serving as a blocking factor. All diets were fed in five phases with the same corn-soybean meal-based diets containing 20% dried distiller’s grains with solubles. Experimental treatments were the same as in

Exp. 1 with: (1) corn ground to 685 μ using 2 sets of rolls (2-High); (2) corn ground to 577 μ using 3 sets of rolls (3-High); (3) corn ground to 360 μ using 4 sets of rolls in a fine grind configuration (4-High fine); and (4) corn ground to 466 μ 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. Diets were fed in a 5-phase feeding program, formulated for 70 to 100, 100 to 140, 140 to 180, 180 to 230, and 230 to 280 lb.

Pigs were weighed and feed disappearance 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. 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 NPPC (1991) guidelines for lean containing 5% fat: Lean % = (2.83 + (0.469 × (HCW)) - (1847 × (fat depth)) + (9.824 × loin depth)) / (HCW).

Caloric feed efficiencies were determined on both an ME and NE basis (NRC, 2012). Efficiencies 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. Feed cost/pig, feed cost/lb gain, revenue per pig, and IOFC were calculated to determine economic implications. 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 = 2-High ($0.00/ton corn), 3-High ($0.175/ton corn), 4-High Fine ($0.645/ton corn), 4-High Coarse ($0.246/ton corn). 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 ground corn. The supplemental grinding electricity cost was drawn from the additional electricity cost above the 2-High baseline cost of $0.3663/ton ground corn, which was included in the grind/mix/delivery fee. Feed cost/pig was determined by total feed intake × diet cost ($/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 live gain, and IOFC was calculated using revenue/pig – feed cost/pig.

Electricity data was collected for all roller mill configurations on 23 occasions, 20 dates of experimental diet manufacture and 3 capacity tests to accurately determine throughput using the treatment configurations. Corn ground during the capacity tests was used in manufacture of non-test 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 of experimental diet manufacture 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 every grinding rolls for more 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 12). . 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 13) includes the samples collected during the 3 capacity tests, as well as the 3 dates of diet manufacture which collected samples between each grinding roll.

In all 3 experiments, complete diet samples were collected from feeders within treatment at multiple locations, subsampled, and submitted to Ward Laboratories, Inc. (Kearney, NE) for analysis of DM, CP, ADF, crude fiber, Ca, P, fat, ash, and starch. 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 ingredients 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 grams of an ingredient falls freely through on three consecutive attempts. Additionally, flowability was measured using angle of repose in which grain was placed in a cylinder on top of a 8.7 cm diameter pedestal. The cylinder was then lifted, which allowed the excess grain is 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, in the K-State Swine Lab 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 for Exp. 1 and 3. For 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 within pen mean difference in ADFI and was expressed as percentage of the total consumed for each diet comparison. For Exp. 3, hot carcass weight was used as a covariate for carcass characteristics other than yield. 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. Results were considered significant at $P \le 0.05$ and a trend at $P \le 0.10$.

Results and Discussion:

Exp. 1 and 2

As expected, chemical analysis of complete diets from both trials revealed no notable differences between treatments within experiment (Table 2). Corn ground using the 2-High configuration had the largest particle size and standard deviation (Table 3). Corn ground using the 3-High configuration and the 4-High coarse configuration had similar mean particle size, however the 3-High mill produced ground corn with a lower standard deviation. The 4-High fine configuration produced the finest particle size corn, as expected, and also had the lowest standard deviation. As particle size was reduced, surface area, expressed as cm^2/gram, increased.

Flowability using the Flowdex device resulted in similar flowability index scores for both 4-High configurations, whereas the 2-High configuration had an improved flowability index score, and the 3-High configuration had the most desirable flowability score (Table 3). The 4-High fine configuration had the least desirable angle of repose flowability score, whereas the 2- and 3-High configurations produced the most desirable ground corn based on angle of repose flowability. As expected, the corn produced from the 4-High fine configuration had the lowest bulk density, whereas the 2-High and 4-High coarse configurations ground corn had the greatest bulk density.

Complete diets for Exp. 1 had similar Flowdex flowability scores for the 2, 3, and 4-High coarse configurations, whereas the 4-High fine configuration has the least desirable flowability score (Table 4). In Exp. 2, the 2-High configuration resulted in the lowest Flowdex flowability score, followed by the 4-High coarse configuration, and the 4-High Fine configuration resulted in the least desirable flowability score. Angle of repose flowability resulted in similar results with the 2-High configuration having the most desirable flowability, and the 4-High fine configuration resulting in the least desirable flowability. As expected, complete diet bulk density was lowest for the 4-High fine configuration, and greatest for the 2-High configuration.

In Exp. 1, there were no differences ($P > 0.05$) in ADG, ADFI, or F/G between roller mill configurations (Table 6). There also were no observed differences ($P > 0.05$) in caloric efficiency or economics among roller mill configurations.

In Exp. 2, pigs consumed more (67%; $P < 0.05$) of the diet containing 2-High roller mill manufactured corn than the diet with 4-High fine corn (33%; Table 6). There was no difference ($P > 0.05$) in feed consumption between the diet containing 2-High roller mill manufactured corn and the diet manufactured with corn from the 4-High roller mill in a coarse configuration (50.3 vs 49.7%, respectively). Pigs consumed more (63%; $P < 0.05$) of the diet manufactured using corn from the 4-

High roller mill in a coarse configuration than the diet using corn from the 4-High mill in a fine grind configuration (37%),.

In summary, nursery pigs preferred diets containing corn ground to 650 μ compared to diets containing corn ground to 340 μ, and preferred diets containing corn ground to 490 μ compared to diets containing corn ground to 340 μ. However, there was no observed difference in feed preference when pigs had access to diets containing corn ground to 650 microns (2-High) compared to 490 microns (4-High coarse). Roller mill ground corn did not show an improvement in growth performance below a particle size of 650 microns in nursery pigs. A 4-High roller mill has the capability to produce a finer grind and reduce particle size below the level possible with previous roller mills and similar to a hammer mill; however, our study did not indicate a benefit in nursery pig performance or economic return when particle size was reduced below 650 μ.

Exp. 3

As expected, chemical analysis of complete diets from both trials revealed no notable differences between treatments within experiment (Tables 8 to 10). 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 lowest particle size whether measured without or with a flow agent (Table 12). Particle size was 65 to 113 microns smaller when measured with a flow agent as compared to measuring without the flow agent with the difference being greatest at the larger 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. 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 13). Flowdex flowability index and angle of repose flowability resulted in inconsistent response as the grain progressed through the roller mill. Surface area increased ($P < 0.05$) as the grain progressed through additional grinding rolls, with the exception of the 2-High configuration. As expected, bulk density decreased ($P < 0.05$) as the grain progressed through additional grinding rolls.

Physical analysis of diets (Table 14) 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.

Corn ground using the 2-High configuration resulted in the lowest ($P < 0.05$) cost/ton ground corn, followed by the 3-High configuration, 4-High coarse configuration, and the 4-High fine configuration resulted in the greatest cost (Table 11). 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.

Pigs fed diets containing corn ground with the 2-High roller mill and the 4-High coarse configuration had the greatest ADG ($P < 0.05$), whereas pigs fed diets with corn ground using the 4-High fine configuration had the poorest ADG (Table 15). Pigs fed diets ground using the 4-High fine configuration had the lowest ($P < 0.05$) ADFI; however, there were no observed 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 observed differences ($P > 0.05$) in yield, backfat, loin depth, or percent lean among roller mill configurations. 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 4-High coarse configurations. IOFC was least ($P < 0.05$) for pigs fed diets ground using the 4-High fine configuration; however, there were no observed 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 μ 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 configurations. Palatability of diets containing corn ground to less than 600 microns appears to be a concern when the diets are fed in meal form. Recent advances in roller mill technology allow producers to achieve a smaller mean particle size than was previously available with roller mills; however, this study indicates particle size reduction below 685 μ with a roller mill did not improve economic return.

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

Item	Exp. 1 and 2
Ingredient, %	
Corn	63.75
Soybean meal	32.85
Monocalcium phosphate	1.10
Limestone	0.98
Salt	0.35
L-lysine HCl	0.30
DL-methionine	0.12
L-threonine	0.12
Vitamin premix	0.25
Trace mineral premix	0.15
Phytase[2]	0.015
Total	100
Calculated analysis[3]	
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/lb	1,484
NE, kcal/lb	1,092
SID lys:ME, g/Mcal	3.73
SID lys:NE, g/Mcal	5.07
CP, %	21.4
Ca, %	0.70
P, %	0.64
Available P, %	0.41

[1] Treatment diets were fed to 410 pigs (320 DNA 400 × 200, initial BW 24 lb; 90 PIC 327 × 1050, initial BW 27 lb) fed for 21 and 7 d for Exp. 1 and 2, respectively.

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

[3] NRC. 2012. Nutrient Requirements of Swine, 11th ed. Natl. Acad. Press, Washington DC.

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

	Exp. 1, Nursery performance[2]				Exp. 2, Nursery preference		
Item:	2 - High	3- High	4 - High Fine	4 - High Coarse	2 - High	4 - High Fine	4 - High Coarse
DM, %	89.62	89.47	89.36	89.84	89.68	89.47	89.67
CP, %	21.3	20.5	19.1	21.2	21.3	21.2	21.1
ADF, %	1.2	0.9	0.9	1.1	1.7	1.8	1.7
Crude fiber, %	2	1.9	2.1	2.3	2.1	2.0	2.0
NFE, %[3]	60.5	61.4	62.7	60.9	59.8	59.8	60.1
Ca, %	0.66	0.78	0.76	0.72	0.80	0.80	0.85
P, %	0.58	0.60	0.62	0.58	0.62	0.64	0.63
Ether extract, %	2.4	2.3	2.2	2.4	2.5	2.1	2.2
Ash, %	4.40	4.49	4.51	4.5	4.82	4.95	4.88
Starch, %	38.0	39.5	38.8	38.5	36.4	36.2	38.8

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

[2] Corn was ground using 2 sets of rolls (648 µ), 3 sets of rolls (495 µ), 4 sets of rolls in a fine-grind configuration (340 µ), and 4 sets of rolls in a coarse configuration (490 µ).

[3] NFE: nitrogen-free extract.

Table 3. Physical analysis of ground corn, Exp. 1 and 2[1]

Item:	Roller mill configuration[2] 2 - High	3 - High	4 - High Fine	4 - High Coarse
Without flow agent				
Particle size, µm[3]	648	495	340	490
St. dev.	2.42	2.17	2.12	2.24
Particles/gram[4]	95,085	93,947	242,825	121,607
Surface area[5,6]	103.8	124.0	177.0	128.5
With flow agent[7]				
Particle size, µm	525	394	267	403
St. dev.	3.14	2.73	2.57	2.81
Particles/gram	1,902,464	1,156,829	2,148,887	1,420,745
Surface area	166.7	190.9	264.9	192.6
Flowdex, mm[7]	24	22	26	26
Angle of repose	52.00	52.81	57.65	54.36
Bulk density, lb/bu[8]	39.56	37.97	37.75	39.43

[1] A composite sample was collected at O.H. Kruse Feedmill from multiple locations within transport tote at time of diet manufacture.

[2] Corn was ground using 2 sets of rolls (648 µ), 3 sets of rolls (495 µ), 4 sets of rolls in a fine-grind configuration (340 µ), and 4 sets of rolls in a coarse configuration (490 µ).

[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 both flow agent and no flow agent.

[4] Particles/gram is calculated by: (1 / specific weight) ^ ((4.5 × natural log (standard deviation)^2) – (3 × natural log (particle size × 0.0001))).

[5] Expressed in cm^2/gram.

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

[7] 0.50 grams amorphous silica powder (Gilson Company, Inc., Lewis Center, OH) added as sieving agent to 100.0 gram grain sample.

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

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

Table 4. Physical analysis of diets, Exp. 1 and 2[1]

	Exp. 1, Nursery Performance[2]				Exp. 2, Nursery Preference		
Item	2-High	3-High	4-High Fine	4-High Coarse	2-High	4-High Fine	4-High Coarse
Flowdex, mm[3]	24	24	26	24	24	28	26
Angle of repose	52.08	54.12	57.13	55.77	50.45	57.01	52.16
Bulk density, lb/bu[4]	46.92	45.60	45.74	46.55	47.99	47.02	47.35

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

[2] Corn used in diets was ground using 2 sets of rolls (648 µ), 3 sets of rolls (495 µ), 4 sets of rolls in a fine-grind configuration (340 µ), and 4 sets of rolls in a coarse configuration (490 µ).

[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 5. Effects of roller mill configuration on growth performance in nursery pigs, Exp. 1[1,2]

	Roller mill configuration[3]					
Item:	2-High	3-High	4-High Fine	4-High Coarse	SEM	*P* <
BW, lb						
d0	23.6	23.6	23.6	23.6	0.35	1.000
d21	51.4	51.4	51.2	51.3	0.84	0.998
d 0 to 21						
ADG, lb	1.33	1.33	1.28	1.32	0.023	0.479
ADFI, lb	2.06	2.04	1.98	1.98	0.038	0.350
F/G	1.55	1.54	1.54	1.50	0.015	0.122
Caloric efficiency[4]						
ME	2,203	2,283	2,289	2,230	22.6	0.122
NE[5]	1,695	1,680	1,684	1,641	16.6	0.122
Economics[6,7]						
Feed cost/pig, $	4.73	4.68	4.56	4.55	0.086	0.381
Feed cost/lb gain, $[8,9]	0.170	0.169	0.169	0.165	0.0017	0.124
Total revenue/pig, $[10]	16.71	16.70	16.16	16.66	0.289	0.479
IOFC, $[11]	11.98	12.01	11.61	12.10	0.219	0.412

[1] A total of 320 nursery pigs (DNA 400 × 200, initial BW 24 lb) were used in a 21-d study with 5 pigs per pen and 16 replications per treatment.

[2] Unlike superscripts differ significantly ($P < 0.05$).

[3] Corn used in diets was ground using 2 sets of rolls (648 µ), 3 sets of rolls (495 µ), 4 sets of rolls in a fine-grind configuration (340 µ), and 4 sets of rolls in a coarse configuration (490 µ).

[4] Caloric efficiency is expressed as kcal/lb gain.

[5] NRC. 2012. Nutrient Requirements of Swine, 11th ed. Natl. Acad. Press, Washington DC.

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

[7] Diet cost=Base diet cost per phase × (amount of corn/ton) × additional electricity cost above base. Electricity costs by treatment, 2 - High = $0.36/ton ground corn, 3 - High = $0.54, 4 – High Fine = $1.01, 4 – High Coarse = $0.62.

[8] One lb of body gain = $0.60/lb.

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

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

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

Table 6. Effects of roller mill configuration on feed intake preference in nursery pigs, Exp. 2[1,2,3]

Item:	ADFI, lb	ADFI, %[4]
Comparison 1		
2 - High	1.15	67.0
4 - High Fine	0.57	33.0
SEM	0.069	3.88
Probability, *P* <	0.0002	0.0001
Comparison 2		
2 - High	0.89	50.3
4 - High Coarse	0.87	49.7
SEM	0.058	2.95
Probability, *P* <	0.7781	0.882
Comparison 3		
4 - High Fine	0.63	37.1
4 - High Coarse	1.10	62.9
SEM	0.084	3.91
Probability, *P* <	0.0030	0.0009

[1] A total of 90 pigs (PIC 327 × 1050, initial BW 27 lb) were used in a 7-d preference trial with 5 pigs per pen and 6 replications per comparison.

[2] Corn used in diets was ground using 2 sets of rolls (648 μ), 3 sets of rolls (495 μ), 4 sets of rolls in a fine-grind configuration (340 μ), and 4 sets of rolls in a coarse configuration (490 μ).

[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.

Table 7. Diet composition, Exp. 3 (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
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), initial BW 88.3 lb) for a 97-d growth experiment in a 5-phase feeding program.

[2] DDGS = dried distiller's 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 DC.

Table 8. Chemical analysis of diets, Exp. 3, 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 collected directly from all feeders per treatment per phase, subsampled, and submitted to Ward Laboratories (Kearney, NE) for analysis.

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

Table 9. Chemical analysis of diets, Exp. 3, 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 exract, %	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 collected directly from all feeders per treatment per phase, subsampled, and submitted to Ward Laboratories (Kearney, NE) for analysis.

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

Table 10. Chemical analysis of diets, Exp. 3, 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 collected directly from all feeders per treatment per phase, subsampled, and submitted to Ward Laboratories (Kearney, NE) for analysis.

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

Table 11. Roller mill electricity consumption[1,2]

	Roller mill configuration[3]					
Item:	2 – High	3 – High	4 – High Fine	4 – High Coarse	SEM	Probability, $P <$
Grinding rate, ton/hr[4]	13.39[a]	12.07[b]	8.24[c]	14.46[a]	0.4486	0.001
Electricity cost, $/ton[5,6]	0.366[d]	0.541[c]	1.011[a]	0.612[b]	0.0321	0.001

[1] Unlike superscripts differ ($P < 0.05$).

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

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

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

[5] Electricity cost = $/ton ground corn.

[6] Cost of electricity was fixed at $0.13/kWh.

Table 12. Physical analysis of ground corn used in growth trial, Exp. 3[1,2]

Item:	Roller mill configuration[3]: 2 – High	3 – High	4 – High Fine	4 – High Coarse	SEM	Probability, $P <$
Without flow agent						
Particle size, μm[4]	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[5,6]	94.3[d]	111.2[c]	169.0[a]	140.6[b]	4.64	0.001
With flow agent[7]						
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[5,6]	144.1[d]	168.2[c]	240.2[a]	216.3[b]	10.74	0.001
Flowdex, mm[8]	22.61[b]	22.73[b]	24.98[a]	25.23[a]	0.972	0.001
Angle of repose	47.81[c]	50.13[b]	54.71[a]	53.78[a]	0.377	0.001
Bulk density, lb/bu[9]	40.37[a]	39.63[b]	37.53[c]	39.66[b]	0.623	0.001

[1] Unlike superscripts differ ($P < 0.05$).

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

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

[4] 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.

[5] Expressed in cm^2/gram.

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

[7] 0.50 grams amorphous silica powder (Gilson Company, Inc., Lewis Center, OH) added as sieving agent to 100.0 gram grain sample.

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

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

Table 13. Characterization of roller mill ground corn, Exp. 3[1,2]

Item:	Roller mill configuration[3]				SEM
	2 – High[4]	3 – High	4 – High Fine	4 – High Coarse	
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	90.28[g,h,i]	87.93[h,i]	97.52[e,f,g,h,i]	83.52[i]	5.970
Roll 2	101.2[e,f,g,h]	107.23[d,e,f]	109.7[d,e]	104.30[d,e,f,g]	5.970
Roll 3	- - -	131.35[c]	152.50[b]	127.67[c]	5.970
Bottom	94.80[f,g,h,i]	119.05[c,d]	168.67[a]	126.17[c]	5.970
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	183.81[d,e]	168.09[e,f]	193.23[c,d,e]	167.89[e,f]	11.152
Roll 2	173.81[d,e,f]	189.14[d,e]	189.13[d,e]	176.93[d,e]	11.152
Roll 3	- - -	217.68[b,c]	251.88[a]	216.34[b,c]	11.152
Bottom	149.99[f]	179.18[d,e]	236.66[a,b]	196.06[c,d]	11.152
Flowdex index, mm[9,10]					
Roll 1	26.45	25.45	26.78	26.45	0.915
Roll 2	22.78	24.11	23.11	24.45	0.915
Roll 3	- - -	23.78	26.11	25.11	0.915
Bottom	22.45	21.45	24.45	24.78	0.915
Angle of repose					
Roll 1	47.82[f]	48.54[d,e,f]	48.58[d,e,f]	48.16[e,f]	0.693
Roll 2	48.53[d,e,f]	49.91[d,e]	48.98[d,e,f]	50.15[d]	0.693
Roll 3	- - -	54.42[c]	54.78[a,b]	53.09[b,c]	0.693

Bottom	48.61[d,e,f]	50.31[d]	55.30[a]	53.39[a,b,c]	0.693
Bulk density, lb/bu[11]					
Roll 1	42.26[a]	42.41[a]	42.27[a]	42.59[a]	0.535
Roll 2	40.50[b]	40.45[b]	40.36[b]	40.59[b]	0.535
Roll 3	- - -	39.31[c,d]	38.99[d]	40.20[b]	0.535
Bottom	39.86[b,c]	38.93[d]	37.40[e]	39.29[c,d]	0.535

[1] Roller mill configuration × roll location interactive means with unlike 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 µ), 3 sets of rolls (577 µ), 4 sets of rolls in a fine-grind configuration (360 µ), or 4 sets of rolls in a coarse configuration (466 µ).

[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/gram.

[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 14. Physical analysis of diets, Exp. 3[1]

	Roller mill configuration[2]			
Item:	2-High	3-High	4-High Fine	4-High Coarse
Phase 1				
Flowdex, mm[3]	20	20	26	24
Angle of repose	48.60	49.35	50.27	50.45
Bulk density, lb/bu[4]	43.94	43.59	43.33	43.92
Phase 2				
Flowdex, mm[3]	26	28	30	26
Angle of repose	53.13	54.66	56.35	52.81
Bulk density, lb/bu[4]	42.53	41.19	41.56	41.93
Phase 3				
Flowdex, mm[3]	28	28	28	26
Angle of repose	52.65	56.35	57.01	53.45
Bulk density, lb/bu[4]	1.84	41.17	41.07	41.61
Phase 4				
Flowdex, mm[3]	22	22	28	26
Angle of repose	46.81	49.54	53.91	53.45
Bulk density, lb/bu[4]	41.84	40.85	39.98	40.26
Phase 5				
Flowdex, mm[3]	28	24	30	28
Angle of repose	51.83	52.00	54.80	53.29
Bulk density, lb/bu[4]	40.25	40.79	39.18	40.45

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

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

[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 15. Effects of roller mill configuration on growth performance in finishing pigs, Exp. 3[1,2]

Item:	Roller mill configuration[3] 2 - High	3 - High	4 - High Fine	4 - High Coarse	SEM	Probability, *P* <
BW, lb						
d0	88.3	88.3	88.3	88.3	0.78	1.000
d56	214.6[a]	210.9[b]	209.4[b]	210.9[b]	1.13	0.004
d97	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[4]						
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
Carcass characteristics[5]						
HCW, lb	210.5[a]	207.8[a,b]	204.4[b]	207.0[a,b]	1.39	0.036
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, %[6]	52.41	52.20	52.64	52.22	0.256	0.472
Economics[7,8]						
Feed cost/pig, $	55.68[a]	54.02[b]	52.39[c]	53.84[b]	0.417	0.001
Feed cost/lb gain, $[9]	0.264[a]	0.261[a]	0.261[a]	0.259[b]	0.0012	0.078
Revenue/pig, $[10]	126.66[a]	124.08[b]	120.62[c]	124.55[a,b]	0.842	0.001
IOFC, $[11]	70.99[a]	70.06[a]	68.23[b]	70.71[a]	0.571	0.006

[1] Unlike superscripts differ ($P < 0.05$).

[2] A total of 922 finisher pigs (initially 88.3 lb BW) were used in a five phase finisher study with 21 pigs per pen and 11 replications per treatment.

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

[4] 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 DC.

[5] 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.

[6] 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).

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

[8] 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.

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

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

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