Title: Enhancing feed utilization and nutrient digestibility through management of particle size and feed processing options – **NPB #13-037** revised

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Industry summary:

The overall goal for this experiment was to determine the impact of average particle size of corn, wheat and corn DDGS with two different grinding technologies on the digestion of energy and nutrients in growing pigs and finishing pigs. Corn and wheat were ground to three different particle sizes (300, 500, and 700 microns), using either a roller mill or a hammermill for each particle category (making 6 diets per each ingredient). For corn DDGS there were 3 diets, each diet included 51% of corn ground at 500 microns with a roller mill, and then mixed with 45% corn DDGS ground to 450 microns using either a hammer mill or a roller mill, or not further ground (unprocessed particle size was 650 microns). Samples from middle sieve fractions were taken for chemical analysis. A total of 120 growing barrows housed individually and fed the experimental diets for each weight category (Growers = 55 kg and Finishers = 110 kg). Digestibility of dry matter, energy, crude protein, fat and neutral detergent fiber were determined on all samples. Results from corn showed that digestion of dry matter, energy, and crude protein was greater in the finisher compared to the grower pigs. Surprisingly, digestibility of fat was greater in grower as compared to finisher pigs. Lowering mean particle size increased digestibility of energy and nutrients in corn ground with a roller mill but not with a hammer mill. Part of the reason for this interaction may be related to physical differences of the final ground product. Digestion of neutral detergent fiber was influenced by the interaction of body weight, particle size and grinding method. Basically, for growing pigs, lowering particle size of corn with a hammer mill resulted in lower fiber digestibility. However, in finishing pigs, NDF digestibility was similar across particle sizes and processing method. On the other hand, in finishing pigs, lowering particle size of corn using a roller mill resulted in greater fiber digestion when particle size was reduced from 700 to 500 microns; there was no further benefit to reducing particle size to 300 microns. Results from wheat showed that there was an interaction among the three factors evaluated. Growing pigs had improved digestion of dry matter, energy, crude protein, fat and fiber when particle size was lowered from 700 to 500 microns using either a hammer mill or a roller mill. There was no further improvement when particle size was further reduced from 500 to 300 microns. In finishing pigs, digestion of dry matter, energy, crude protein, fat and fiber was improved by lowering mean particle size with a hammer mill from 700 to 500 microns but not to 300 microns. Using a roller mill, digestion of dry matter and fiber decreased by lowering mean particle size from 700 to 300 microns, while digestion of GE was decreased only by lowering mean PS from 700 to 500 microns, with no further benefit to grinding to 300 microns. In corn DDGS, digestion of dry matter, energy and crude protein was greater in finisher pigs compared to growing pigs. Lower particle size improved digestion of dry matter, energy, fat and crude protein irrespective of milling

method. Digestion of fiber in DDGS was not affected by particle size or body weight. In conclusion, mean particle size, grinding method and BW can influence the digestibility of corn, wheat and corn DDGS differently; while smaller particle size was found to be generally better, this did not hold true in all instances. If ingredients can efficiently be ground to different particle sizes, profits can be maximized at the lowest possible processing cost.

Key Findings:

- Overall, reducing mean particle size improved feed utilization in pigs through increased digestibility; however, this did not hold true in all instances.
- Digestibility of corn progressively increased as particle size was reduced (700 to 300 microns) with a roller mill; in contrast, with a hammermill, there was little difference in digestibility across all particle sizes.
- Digestibility of wheat was influenced in 55 kg pigs by reducing particle size only from 700 to 500 microns irrespective of the grinding method used. In contrast, 110 kg pigs showed specific optimal particle size for best digestibility percentages (700 microns for roller mill and 500 microns for hammermill).
- Reducing the mean particle size of corn DDGS either with a hammermill or a roller mill (from 650 to 450 microns) provided only a modest advantage in terms of improved digestibility.

Keywords: Roller mill, hammermill, particle size, body weight

Scientific abstract:

The objective of this study was to determine the impact of mean particle size (PS) of corn, wheat and DDGS with two different grinding technologies on the apparent total tract digestibility (ATTD) of DM, GE, CP, AEE and NDF in growing pigs (GP) and finishing pigs (FP). One hundred and twenty growing barrows (BW= 54.6 ± 0.4 kg) and the same number of finishing barrows ((BW =110.2 ± 0.8); PIC 337 sires x C22 or C29), were housed in individual pens and randomly assigned to 1 of 15 treatments providing 8 observations per dietary treatment. Corn and wheat were ground at three different PS (300, 500, and 700 microns), using either a roller mill (RM) or a hammermill (HM), generating 6 treatments per ingredient. For corn DDGS there were 3 treatments. Each DDGS diet contained 51% of corn ground at 500 microns with a RM, and then mixed with 45% of corn DDGS ground at 450 microns using HM, or ground at 450 microns using a RM or not further ground (unprocessed) at 650 microns. Mean and standard deviation of PS were determined using a sieve shaker. Samples from middle sieve fractions were collected for further laboratory analyses. Fecal samples were collected for the last three days of an 11d feeding period. Titanium dioxide was used as indigestible marker. Digestibility data were analyzed using the MIXED procedure of SAS. In corn, grinding method interacted with PS (P<0.001), suggesting that reducing the mean PS of corn with a RM (from 700 to 300 microns) increased ATTD of DM (P<0.05), GE (P<0.05) and CP (P<0.05); however, decreasing mean PS of corn with a HM had little to no effect on these same parameters (P>0.05). GP had greater ATTD of AEE than FP (P<0.001), while grinding method interacted with PS (P<0.001); this interaction suggest that reducing corn mean PS from 500 to 300 microns, but not from 700 to 500 microns with a roller mill, result in greater ATTD of AEE. In contrast, corn ground with a hammermill result in similar ATTD of AEE from 700 to 300 microns (P>0.05). For ATTD of NDF, there was a three way interaction among BW period, grinding method and PS (P=0.003); GP fed corn ground with a HM presented lower ATTD of NDF as micron size was reduced (from 700 to 300 microns; P<0.05). However, GP fed corn ground with RM had greater ATTD of NDF when PS was reduced from 700 to 500 microns (P<0.05), but similar from 500 to 300 microns (P>0.05). FP fed corn ground to a lower PS (from 700 to 300 microns) with a HM had similar ATTD of NDF (P>0.05). FP fed corn ground with a RM had greater digestibilities for 700 than for 500 microns (*P*<0.05); however, digestibility was similar for 500 and 300 microns (*P*>0.05). Results from wheat showed that ATTD of DM, GE, CP, AEE and NDF were influenced by the interaction among BW period, grinding method and PS (*P*<0.001, *P*<0.001, *P*<0.001, *P*<0.001 and *P*<0.001 respectively); GP had greater ATTD of DM, GE, CP, AEE and NDF by lowering mean PS with a HM or a HM from 700 to 500 microns (*P*<0.05). However, there was no further increase from 500 to 300 microns (*P*>0.05), except for AEE (*P*<0.05). FP pigs had greater ATTD of DM, GE, CP, AEE and NDF by lowering mean PS with a HM from 700 to 500 microns (P<0.05), but it was greater for 500 than for 300 microns (*P*<0.05). Using a RM ATTD of DM and NDF decreased by lowering PS from 700 to 300 microns (P<0.05). For ATTD of GE was decreased by lowering PS from 700 to 500 microns (*P*>0.05), but was similar from 500 to 300 microns (*P*<0.05). Finally, ATTD of CP and AEE were similar from 700 to 300 microns (*P*>0.05). Results from corn DDGS showed that GP had greater ATTD of DM, GE and CP (*P*=0.09, *P*=0.026, *P*<0.0001 respectively), but ATTD of AEE and NDF were similar between GP and FP (*P*=0.391 and P=0.335 respectively). There were significant differences among treatments for ATTD of DM, GE, and AEE (*P*<0.001, *P*<0.001 and *P*<0.001 respectively) and ATTD of CP tend to be different among treatments (*P*=0.090); resulting in greater digestibility for DDGS at 650 than at 450 microns; *P*<0.05, and not being influenced by grinding method (at 450 microns; *P*>0.05). In conclusion, mean particle size, grinding method and BW can influence the digestibility of corn, wheat and corn DDGS differently; while smaller particle size was found to be generally better, this did not hold true in all instances. If ingredients can efficiently be ground to different particle sizes, profits can be maximized at the lowest possible processing cost.

Introduction:

Digestion is essential because it determines the uptake of nutrients and energy from the diet. Great efforts have been exerted over the years to optimize the process of digestion. One of the many options to achieve this objective is to reduce the particle size of feed ingredients. Theoretically, this reduction improves digestion by increasing the surface area, facilitating enzyme action (Wondra et al., 1995). However, there are at least three major factors to be better understood: first, to find an optimum PS; most research to date looked at particle size ranges from 500 microns or 600 microns and up, while the industry is working at, or seeking to work at, levels well under this. Second, a reduction of particle size is achieved by grinding feed material mainly using two grinding models or techniques: a roller mill or a hammermill. These techniques deliver different particle shapes; this can imply different responses in digestion by the pig (Wondra et al., 1995). Third, digestion is believed to improve as animals grow. A more developed gastrointestinal tract has greater digestion capacity, especially the fiber fraction (Noblet and Shi, 1993). Finally, there is also interest in the variation in particle size, but there is very little data on the nutrient composition of various sieve fractions.

Therefore, definitive data is needed on the impact of particle size within the range of current industry practice (300 to 600 microns), studied at different ages of pigs and comparing hammer versus roller milling. In addition, there is a need for information on particle size variation as mean particle size changes.

Objectives

Main: To develop a more thorough understanding of the role of mean particle size and particle distribution, and method of processing, on nutrient and energy digestibility in the pig

Specific objectives:

1. To determine the impact of mean particle size on the apparent total tract digestibility (ATTD) of energy, dry matter, crude protein and neutral detergent fiber of corn, wheat and corn DDGS.
2. To determine the impact of the age of the pig on the response to particle size reduction.
3. To determine if the impact of mean particle size is the same across the three ingredients and whether it was achieved using both a hammer mill and a roller mill.

4. To identify the composition (dry matter, gross energy, crude protein, fat, neutral detergent fiber and starch) that exists across the profile of particle sizes, namely <1190 µm, 1190 to 840 µm, 840 to 590 µm, 590 to 420 um, and <420 µm.

Materials & Methods:

All procedures used in this experiment were approved by the Iowa State University Institutional Animal Care and Use Committee (#2-14-7731-S). The experiment began on February 24, 2014 and was completed on June 13, 2014.

Animals housing and experimental design:

This experiment was conducted at the Swine Nutrition Farm (Iowa State University Ames, IA). Two groups of 60 barrows (initial BW 54.6±3.9 kg) of the progeny of PIC 337 sires x C22 or C29 dams (Hendersonville, TN) were randomly assigned to one of the fifteen treatments for two periods. A growing period (55 kg BW) and a finishing period (110 kg BW).

Pigs were housed in a controlled environment in individual pens for 11 days (during each period). Each pen included a partially slatted concrete floor, an automatic self-feeder and a cup drinker. Pigs had *ad libitum* access to water, but restricted access to feed. A calculated daily feed ration that provided 2.5 times the daily maintenance energy requirement for the two BW categories was offered. Feed was delivered two times a day (8:00h and 16:00h) in equal sized meals.

Pigs were not fed the same diet in the growing period as they were in the finishing period.

Diets

Diets were manufactured at O.H. Kruse Feed Technology Innovation Center (Kansas State University, Manhattan, KS) using commercial sources of corn, wheat and corn DDGS according to the following specifications: Corn and wheat were ground at 300, 500 and 700 microns, using a hammer mill or a roller mill for each particle size category (making 6 diets per each ingredient). For corn DDGS, there were 3 diets. Each diet consisted of 51% corn ground at 500 microns with a roller mill, and 45% of corn DDGS ground at 450 microns using a hammermill, or 45% corn DDGS ground at 450 microns using a roller mill or 45% of corn DDGS not further ground (unprocessed) at 650 microns.

All diets contained titanium dioxide at 0.4% as an indigestible marker and supplementary vitamins and minerals in order to meet or exceed vitamin and mineral requirements for barrows in the two weight categories. Nevertheless, all diets were considered incomplete, since they did not meet all the specifications for amino acids requirements reported in the NRC (2012).

Data and samples

Particle size distribution was measured using a sieve shaker (model Ro-Tap RX−26, W. S. Tyler, Mentor, OH) equipped with 13 sieves (U.S. standard sieve Nos. 6, 8, 12, 16, 20, 30, 40, 50, 70, 100, 140, 200 and 270) and a pan. The sieve sizes determined the particle size categories, which are reported in g per 100 g retained on the smaller screen: 3.35 mm and larger (3.35 mm), 2.36 to 3.35 mm (2.36 mm), 1.70 to 2.36 mm (1.70 mm), 1.18 to 1.70 mm (1.18 mm), 0.84 to 1.18 mm (0.84 mm), 0.60 to 0.84 mm (0.60 mm), 0.40 to 0.60 mm (0.40 mm), 0.30 to 0.40 mm (0.30 mm), 0.21 to 0.30 mm (0.21 mm), 0.15 to 0.21 mm (0.21 mm), 0.11 to 0.21 mm (0.11 mm), 0.07 to 0.11 mm (0.07 mm),), 0.05 to 0.07 mm (0.05 mm), and less than 0.05 mm, respectively. Samples from middle sieve fractions (sieves Nos. 20, 30, 40, 50 and 70) were collected for further laboratory analyses. Mean particle size and standard deviation were calculated using the diameter of the particle and the weight of the sample retained between sieves.

All pigs were individually weighed on days 0 and 11 at each weigh period. Feed consumption was monitored for each meal as the weight of original feed delivered minus orts (the weight of feed removed from the feeder after 1h of feed allowance).

Fecal samples were taken on days 9, 10, and 11 in pre-labeled plastic bags, being immediately frozen at -20°C after collection. Once collection was completed, fecal samples were homogenized, dried in an oven at 105°C, and finely ground in a Wiley grinder (Model ED-5, Thomas Scientific Inc., Swedesboro, NJ). Feed samples were ground in a Retsch grinder (Model ZM1, Retsch Inc., Newton, PA). All fecal, feed and sieve fraction samples were kept in plastic bags in desiccator cabinets until all chemical assays were completed.

Samples of sieve fractions, feed and feces were analyzed at the Monogastric Nutrition Laboratory (Iowa State University-Ames, IA). Assays included concentration of dry matter using a drying oven (method 930.15; AOAC, 2007), CP as N X 6.25 using combustion (Nitrogen determinator; model TruMac N, Leco Corporation, St. Joseph, MI; method 990.03; AOAC, 2007), EDTA (9.57% nitrogen; Leco Corporation, St. Joseph, MI) was used as standard for calibration and during the assays, was determined to be 9.58 ± 0.02. Acid hydrolyzed ether extract was assayed using a SoxCap hydrolyzer (model SC 247) and a Soxtec fat extractor (model 255), Foss, Eden Prairie, MN (method 968; AOAC, 2007), starch (only analyzed for diets and sieve fractions) was analyzed using Megazyme total starch assay kit analysis, Wicklow, Ireland (modified method 996.11, AOAC 1996), acid and neutral detergent fiber (ADF [only for feed and fecal samples] and NDF were determined using Ankom automated fiber analyzer; model 2000, Macedon, NY (according to Van Soest and Robertson, 1979). Gross energy was determined using a bomb calorimeter; model 6200 Parr Instrument Co., Moline, IL), Benzoic acid (6318 kcal/kg; Parr instruments, Moline, IL) was used as the standard for calibration and was determined to be 6323 ± 8.2 kcal/kg. Titanium dioxide (only for feed and fecal samples) was determined using a spectrophotometer; model Synergy 4, BioTek, Winooski, VT (according to the method of Leone, 1973). ATTD of DM, GE, CP, EE, ADF and NDF was calculated using the equation (Oresanya et al., 2008):

ATTD, % = [100 – [100 * (% TiO_2 in feed / % TiO_2 in feces) x (concentration of component in feces / concentration of component in feed)]]

Statistical Analysis:

The ROBUSTREG procedure of SAS (SAS Inst., Inc., Cary, NC) was used to analyze for outliers. Corn and wheat data were analyzed using PROC MIXED according to the following model: main (fixed) effects of grinding method, particle size and BW period. Corn DDGS data were analyzed using PROC MIXED according to the following model: main (fixed) effects of treatment and BW period. Differences were considered statistically significant with $P \leq 0.05$ and trends from $P > 0.05$ to $P \leq 0.10$. Pig was the experimental unit in all analyses.

Results:

Results of the analyzed chemical composition of the sieve fractions of corn, wheat and corn DDGS are listed in tables 6, 7, 8, 9 and 11. They showed that there was good agreement between the target particle size and that actually achieved in the final sample.

Corn

Finishing pigs fed corn diets showed greater ATTD of DM, GE and CP than growing pigs (P=0.028, P=0.018 and P<0.001 respectively). Grinding method interacted with particle size (P<0.001), suggesting that as mean particle size of corn is reduced with a roller mill (from 700 to 300 microns) there is greater ATTD of DM (P<0.05), GE (P<0.05) and CP (P<0.05). However, decreasing mean particle size of corn with a hammermill had little to no effect on these same parameters (P>0.05; differences were only for GE from 700 to 500 microns in the finishing period; P<0.05).

Opposite to the other variables evaluated, ATTD of AEE was greater for growing pigs than for finishing pigs (P<0.001). On the other hand, similar to the other parameters there was an interaction between grinding method and particle size (*P*<0.001); this interaction suggests that reducing corn mean particle size from 500 to 300 microns, but not from 700 to 500 microns with a roller mill, resulted in greater ATTD of AEE. In contrast, corn ground with a hammermill resulted in similar ATTD of AEE from 700 to 300 microns (*P*>0.05).

For ATTD of DM, GE, CP and AEE there were no interactions between BW period and grinding method (*P*=0.532, *P*=0.335, *P*=0.283 and *P*=0.132 respectively), BW period and mean particle size (*P*=0.273, *P*=0.146, *P*=0.901 and *P*=0.048 respectively), or among BW period, grinding method and mean particle size in corn diets (*P*=0.227, *P*=0.377 *P*=0.184 and *P*=0.825 respectively).

The ATTD of NDF was higher for finishing pigs than for growing pigs (*P*<0.001). BW period interacted with grinding method and particle size (*P*=0.003). Growing pigs fed corn ground with a hammermill presented lower ATTD of NDF as micron size was reduced (from 700 to 300 microns; *P*<0.05). Opposite results were observed for ATTD of NDF when corn was ground with a roller mill, being greater from 700 to 500 microns (*P*<0.05), but similar from 500 to 300 microns (*P*>0.05). Finishing pigs fed corn ground a lower particle size (from 700 to 300 microns) with a hammermill had similar ATTD of NDF. Finishing pigs fed corn ground with a roller mill had greater digestibilities for 700 than for 500 microns (*P*<0.05); however, digestibility was similar for 500 and 300 microns (*P*>0.05).

Wheat

For wheat diets, the ATTD of DM, GE, CP, AEE and NDF were influenced by the interaction among the three factors evaluated (BW period, grinding method and mean particle size *P*<0.001, *P*<0.001, *P*<0.001, *P*<0.001, and *P*<0.001 respectively). Pigs in the growing period increased ATTD of DM, GE, CP, AEE and NDF with a smaller mean particle size from a hammermill from 700 to 500 microns (*P*<0.05). However, there was no further increase from 500 to 300 microns (*P*>0.05; except for AEE *P*<0.05). Using a roller mill, there were similar results; ATTD of DM, GE, CP, AEE and NDF were also increased when mean particle size decreased from 700 to 500 microns (*P*<0.05) but they had no significant increase in digestibility from 500 to 300 microns (*P*>0.05). Digestibility coefficients for each mean particle size category in the growing period for all variables evaluated were always numerically greater for wheat ground with hammermill than with a roller mill. In the finishing period, pigs had greater ATTD of DM, GE, CP, AEE and NDF by lowering mean particle size with a hammermill from 700 to 500 microns (*P*<0.05), but it was greater for 500 than for 300 microns (*P*<0.05).

Using a roller mill, the ATTD of DM and NDF decreased by lowering mean particle size from 700 to 300 microns (*P*<0.05). The ATTD of GE was decreased by lowering mean particle size from 700 to 500 microns (*P*>0.05), but was similar from 500 to 300 microns (*P*<0.05). Finally, ATTD of CP and AEE were similar from 700 to 300 microns (*P*>0.05).

Corn DDGS

For corn DDGS diets, the ATTD of DM significantly improved with a lower mean particle size (from 650 to 450 microns; *P*<0.05), and was not influenced by grinding method (at 450 microns; *P*>0.05). Finishing pigs tended to have better ATTD of DM than growing pigs (*P*=0.091).Although there were no significant differences in the growing period, the ATTD of GE was higher for corn DDGS ground at 450 than at 650 microns in the finishing period (*P*<0.05) and was not influenced by grinding method (at 450 microns; *P*>0.05). Finishing pigs had greater ATTD of GE than growing pigs (*P*=0.026). The ATTD of CP was higher for finishing than growing pigs (*P*<0.01); the ATTD of CP tended to differ among treatments (*P*=0.09) suggesting lower coefficients for diets including corn DDGS ground at 650 microns than those ground at 450 microns. The ATTD of AEE was higher for corn DDGS ground at 450 than at 650 microns (*P*<0.05) and was not similar between grinding methods (at 450 microns; *P*>0.05). Additionally, ATTD of AEE was similar for growing and finishing pigs (*P*=0.391). ATTD of NDF was not different among treatments (*P*=0.770) and BW period (*P*=0.963). There were no interactions between BW period and treatment for ATTD of DM, GE, CP, AEE and NDF in corn DDGS diets (*P*=0.435, *P*=0.115, *P*=0.494, 0.956 and 0.917 respectively).

Discussion:

Corn and wheat are main ingredients in swine diets, with a large proportion of starch (more than 60%), they are characterized as being energy providers. On the other hand, corn DDGS are a good source of protein, and to some extent fat (depending on processing), but also they bring important amounts of fiber to the diet. Chemical composition of corn DDGS is more variable than for corn or wheat due to different methods and production processes (Stein and Shurson, 2009).

Determination of the mean and standard deviation of particle size as well as the sieve fraction analysis is based on an assumption that the particles are able to pass through square holes with a progressive, reduced sieve diameter (Liu, 2011). In roller mill produced corn and wheat, sieves No. 20 and 30 contained very low starch levels, and NDF values were very high. Otherwise, the chemical composition of the 5 sieve fractions tested were within the normal range reported in the feed ingredient composition for corn yellow dent, corn DDGS (>6 and <9% oil) and hard red wheat, reported in the (NRC, 2012).

The mean particle size and grinding method can influence digestibility of ingredients and diets. Reducing mean particle size can improve feed utilization in pigs through increased digestibility (Wondra1995; Gieseman 1990) by increasing the surface area, facilitating enzymatic action. This can be achieved mainly by two grinding methods (roller and hammermill) which may also result in different digestibilities at the same mean particle size (Wondra et al. 1995). Results in this experiment confirmed both effects. First, an inverse relationship between mean particle size (up to 300 micorns) and ATTD of DM, GE and CP was confirmed for corn ground with a rollermill, but not with a hammermill. Part of the reason for this interaction may be related to physical differences of the final ground products. It has been reported that roller mills grind cereals more uniformly and produce a lower amount of fines than hammer mills (NIR et al., 1990; Svihus et al., 2004). Additionally, particles of hammermilled corn have been described as more spherical in shape than roller milled corn (Reece et al., 1985). This shape can reduce the access to digestive enzymes thereby reducing digestibility (Hancock and Behnke, 2001). However, despite a weak relationship between particle size and ATTD of DM, GE and CP, hammermilled corn digestibilities were actually advantageous for 700 microns, similar to the roller mill response for 500 microns, but less useful than roller milled corn at 300 microns.

Second, digestibility can be higher for finishing pigs than for growing pigs (Noblet and Shi, 1993). Results of this experiment confirm that the ATTD of DM, GE and CP in corn are higher with a heavier BW. Our data suggests that this increase occurs independently of the mean particle size or the grinding method.

Results from wheat suggest an interaction among the three factors evaluated. Interpretation of these results became difficult mainly because there is not comparable data However, it is clear that these interactions are being influenced by the finishing period particularly at 500 microns for the hammermill and 700 microns for the roller mill. One possible reason for this effect can be a specific adaptation for finishing pigs to better digest wheat at those particle sizes.

The ATTD of CP, GE and in a minor proportion DM in corn DDGS diets are driven by BW, being higher for finishing pigs than for growing pigs, while mean particle size (from 650 to 450 microns) tended to improve ATTD modestly. ATTD of CP is of great interest for corn DDGS because it is a significant supplier of CP in diets for pigs.

Implications

Based on these results, the selection of the optimal particle size is dependent on the size of the pig, the method of grinding, the nutrient in question and the method of grinding. It is clear that mean particle size, grinding method and BW can also influence the digestibility of corn, wheat and corn DDGS differently; while smaller particle size was found to be generally better, this did not hold true in all instances. If ingredients can efficiently be ground to different particle size targets, profits can be maximized at the lowest possible processing cost.

Table 1. Ingredient composition of experimental diets (as-fed basis) fed to growing (55 kg BW) and finishing pigs (110 kg BW).

Ingredient, %	Corn diets	Wheat diets	Corn+corn DDGS diets
Corn	96.43	-	51.91
Wheat	-	96.87	-
Corn DDGS	-	-	45.00
Monocalcium phosphate	1.08	0.48	0.35
Calcium carbonate	1.19	1.35	1.44
Salt	0.50	0.50	0.50
Vitamin premix	0.20	0.20	0.20
Mineral premix	0.20	0.20	0.20
Titanium dioxide	0.40	0.40	0.40
Total	100.00	100.00	100.00

Table 2. Analyzed chemical composition (as-fed basis) of corn diets fed to growing (55 kg BW) and finishing pigs (110 kg BW)

	Hammermill			Roller mill		
Particle size, microns	300	500	700	300	500	700
DM, %	89.78	89.35	89.38	89.68	89.92	90.18
GE, Mcal/ kg	3.731	3.736	3.727	3.703	3.738	3.721
CP, %	8.34	8.24	8.38	8.02	7.76	7.71
AEE, %	2.32	3.16	3.13	2.31	2.27	3.02
Starch, %	60.84	64.26	65.59	60.55	61.60	61.87
ADF, %	2.55	2.6	2.61	2.3	2.72	2.49
NDF, %	6.76	7.17	7.95	6.48	6.83	6.64

Table 3. Analyzed chemical composition (as-fed basis) of wheat diets fed to growing (55 kg BW) and finishing pigs (110 kg BW)

	Hammermill			Roller mill		
Particle size, microns	300	500	700	300	500	700
DM, %	90.82	90.67	90.3	91.2	90.5	90.73
GE, Mcal/ kg	3.758	3.785	3.767	3.758	3.773	3.731
CP, %	13.24	13.8	13.97	11.17	11.3	11.18
AEE, %	1.85	1.9	1.77	1.93	1.9	1.8
Starch, %	56.66	61.90	57.24	58.75	62.53	60.34
ADF, %	2.59	2.59	2.64	3.17	2.7	2.91
NDF, %	9.37	9.66	9.39	10.02	9.86	9.62

Table 4. Analyzed chemical composition (as-fed basis) of corn DDGS diets fed to growing (55 kg BW) and finishing pigs (110 kg BW)

Item	Corn+corn DDGS hammermill 450 microns	Corn+corn DDGS roller mill 450 microns	Corn+corn DDGS unprocessed 650 microns
DM, %	91.15	91.13	90.90
GE, Mcal/ kg	4.047	4.064	4.061
CP, %	16.48	16.64	17.41
AEE, %	5.02	5.22	5.21
Starch, %	40.87	41.11	39.07
ADF, %	5.35	5.40	5.64
NDF, %	14.15	14.05	15.07

Table 5. Determined mean and standard deviation of corn and wheat particle size using roller mill and hammermill grinding techniques

	Corn		Wheat	
Item	Hammermill	Roller mill	Hammermill	Roller mill
Mean particle size (microns)				
Small (300)	305	275	278	277
Medium (500)	499	496	477	486
Large (700)	710	680	725	783
Standard deviation				
Small (300)	2.9	2.1	2.7	2.7
Medium (500)	3.5	2.5	2.8	2.7
Large (700)	3.4	2.6	3.1	2.4

Table 6. Analyzed chemical composition of sieve fractions of corn using a hammermill

Item	DM, %	GE, Mcal/ kg	CP, %	AEE, %	NDF, %	Starch, %
300 microns						
Sieve No. 20	89.77	4.053	9.12	4.51	8.28	67.24
30	90.09	4.032	9.00	3.67	7.64	56.34
40	89.69	4.014	8.72	3.36	8.85	56.70
50	90.60	4.040	8.69	3.36	9.06	58.70
70	91.38	4.062	8.59	3.56	7.76	64.28
500 microns						
Sieve No. 20	90.24	4.026	10.73	4.65	7.40	64.89
30	89.40	4.011	8.70	3.57	9.37	59.86
40	89.78	4.058	7.99	3.23	9.98	56.03
50	90.31	4.043	9.88	3.38	9.97	55.63
70	91.54	4.051	8.39	3.29	7.99	68.32
700 microns						
Sieve No. 20	88.78	4.049	9.23	4.51	7.56	63.49
30	89.23	3.931	9.06	3.37	10.91	57.30
40	89.72	3.944	8.70	3.78	11.07	62.98
50	89.89	4.038	8.48	3.08	10.90	67.31
70	90.35	4.058	8.23	3.21	8.73	63.96

Table 7. Analyzed chemical composition of sieve fractions of corn using a roller mill

Item	DM, %	GE, Mcal/ kg	CP, %	AEE, %	NDF, %	Starch, %
300 microns						
Sieve No. 20	92.82	4.196	7.84	3.64	61.43	20.22
30	90.43	4.149	10.73	5.95	15.20	53.68
40	90.00	4.042	9.28	3.89	6.60	64.24
50	89.91	3.946	8.70	3.66	4.96	64.70
70	90.05	3.946	7.99	3.15	3.95	66.41
500 microns						
Sieve No. 20	89.58	4.057	9.88	5.16	9.85	61.18
30	89.15	3.985	8.30	3.43	5.27	62.59
40	89.80	3.967	7.68	3.33	5.64	66.04
50	90.90	4.042	7.73	3.78	7.20	62.15
70	92.11	4.047	7.67	3.90	6.94	68.12
700 microns						
Sieve No. 20	91.06	4.056	8.94	4.30	7.48	65.68
30	89.70	3.969	9.28	3.23	8.33	61.92
40	90.97	4.048	7.95	3.45	7.77	64.86
50	90.39	4.016	7.83	3.92	9.17	59.85
70	90.24	4.060	7.85	3.81	8.92	55.64

Table 8. Analyzed chemical composition of sieve fractions of wheat using hammermill

Item	DM, %	GE, Mcal/ kg	CP, %	AEE, %	NDF, %	Starch, %
300 microns						
Sieve No. 20	91.86	3.961	14.27	1.90	9.54	57.24
30	91.66	4.010	14.88	2.13	11.94	56.01
40	92.08	3.993	14.43	2.26	11.05	57.54
50	92.02	3.956	13.74	2.05	10.37	56.13
70	92.43	3.962	13.23	1.94	9.46	58.26
500 microns						
Sieve No. 20	90.03	3.935	14.74	1.64	8.81	57.09
30	90.64	3.969	15.20	2.26	10.28	52.37
40	90.76	3.926	14.57	2.26	10.78	53.51
50	91.58	3.988	13.88	2.17	11.01	55.13
70	91.62	4.031	13.55	2.20	10.12	56.19
700 microns						
Sieve No. 20	91.22	3.914	14.45	1.90	8.13	55.80
30	91.18	3.992	15.85	2.67	11.05	50.54
40	90.90	4.011	14.78	2.44	12.49	49.70
50	90.68	3.989	14.20	2.51	14.14	53.00
70	90.52	4.031	14.16	2.26	14.12	54.00

Table 9. Analyzed chemical composition of sieve fractions of wheat using a roller mill

Item	DM, %	GE, Mcal/ kg	CP, %	AEE, %	NDF, %	Starch, %
300 microns						
Sieve No. 20	91.83	4.112	13.42	2.76	26.15	41.67
30	91.55	4.084	13.68	3.02	20.57	45.45
40	91.48	4.010	13.19	2.88	13.42	52.18
50	91.51	3.937	11.92	2.48	7.69	60.48
70	91.57	3.965	11.16	2.11	4.98	65.85
500 microns						
Sieve No. 20	90.58	3.972	12.45	2.37	13.34	55.44
30	90.80	3.966	12.35	2.65	10.61	57.51
40	91.43	3.961	10.83	2.09	7.98	63.19
50	91.70	3.971	10.19	1.91	7.98	58.36
70	91.99	3.978	9.95	1.91	7.79	62.58
700 microns						
Sieve No. 20	91.06	3.943	11.87	2.28	10.67	55.40
30	91.26	3.989	12.31	2.74	10.41	57.72
40	93.27	3.918	10.70	2.10	9.80	63.98
50	93.16	3.947	10.16	1.85	11.10	58.30
70	92.97	3.961	10.02	1.81	10.32	61.40

Table 10. Determined mean and standard deviation of corn DDGS particle size using roller mill, hammer mill or not post grinding technologies

	Hammermill	Roller mill	Unprocessed
Item		Corn+corn DDGS	
Mean particle size (microns)			
Medium (450)	429	426	-
Large (650)	-	-	670
Standard deviation			
Medium (450)	2.3	2.1	-
Large (650)	-	-	2.3

Table 11. Chemical composition of sieve fractions of corn DDGS

Item	DM, %	GE, Mcal/ kg	CP, %	AEE, %	NDF, %	Starch, %
Hammermill 450 microns						
Sieve No. 20	92.23	4.783	27.98	10.08	26.44	13.48
30	92.09	4.642	28.16	9.32	29.85	12.59
40	91.92	4.630	28.62	8.37	31.05	11.70
50	91.96	4.668	29.00	7.55	29.99	12.41
70	92.39	4.649	30.57	7.38	27.79	12.33
Roller mill 450 microns						
Sieve No. 20	92.35	4.668	24.84	7.94	34.26	12.56
30	91.49	4.656	29.09	9.31	25.77	13.87
40	92.22	4.621	30.56	8.54	24.82	12.99
50	92.38	4.726	31.47	7.97	25.71	12.35
70	92.90	4.711	32.80	7.10	24.59	13.25
Unprocessed 650 microns						
Sieve No. 20	92.98	4.784	28.89	10.01	25.43	12.28
30	92.83	4.726	28.82	8.82	26.42	10.76
40	92.72	4.715	29.89	7.62	29.04	11.11
50	92.24	4.727	31.07	7.75	29.27	10.78
70	92.92	4.652	33.02	7.37	25.58	11.30

Table 12. Apparent total tract digestibility of DM, GE, CP, AEE and NDF of corn ground at 300, 500 and 700 microns, using either roller mill or hammermill

Item			ATTD, %				
Period	Grinding method	Particle size	DM	GE	CP	AEE	NDF
55 kg, BW	Hammermill	300	84.5^{fg}	83.0^{de}	66.9^{de}	24.9^{bc}	32.8^{e}
		500	85.6d^{ef}	83.3^{de}	69.3^{d}	27.0^{abc}	43.7^{cd}
		700	85.7^{def}	83.3^{de}	67.6^{de}	32.5^{ab}	51.6^{ab}
	Roller mill	300	88.2^{ab}	87.5^{ab}	74.9^{b}	36.4^{a}	49.5^{bc}
		500	86.2^{cde}	84.2^{d}	66.9^{de}	2.5^{fgh}	43.6^{cd}
		700	83.0^{h}	80.3^{g}	56.3^{f}	8.1^{efg}	32.1^{e}
110 kg, BW	Hammermill	300	85.9^{def}	84.6^{cd}	74.4^{bc}	11.7^{def}	51.5^{ab}
		500	86.4^{cd}	84.3^{cd}	74.8^{b}	20.3^{cd}	48.1^{bcd}
		700	84.9^{efg}	82.2^{ef}	70.4^{cd}	13.9^{de}	46.8^{bcd}
	Roller mill	300	88.7^{a}	88.6^{a}	80.0^{a}	32.8^{ab}	56.5^{a}
		500	87.3^{bc}	85.9^{bc}	74.8^{b}	0.6^{gh}	51.9^{ab}
		700	83.8^{gh}	81.1^{fg}	64.9^{e}	-6.4^{h}	41.1^{d}
Pooled SEM			0.5	0.6	1.5	3.5	2.5
Source of variance							
Period			0.028	0.018	<0.001	<0.001	<0.001
Grinding method			0.009	0.002	0.302	<0.001	0.971
Particle size			<0.001	<0.001	<0.001	<0.001	0.025
Period x grinding method			0.532	0.335	0.283	0.132	0.479
Period x size			0.273	0.146	0.901	0.048	0.013
Grinding method x size			<0.001	<0.001	<0.001	<0.001	<0.001
Period x grinding method x size			0.227	0.377	0.184	0.825	0.003

Table 13. Apparent total tract digestibility of DM, GE, CP, AEE and NDF of wheat ground at 300, 500 and 700 microns, using either roller mill or hammermill

Item			ATTD, %				
Period	Grinding method	Particle size	DM	GE	CP	AEE	NDF
55kg, BW	Hammermill	300	87.4^{b}	87.0^{b}	84.1^{cd}	46.1^{ab}	52.9^{ab}
		500	86.7^{bcd}	86.1^{bcd}	83.8^{d}	36.9^{cd}	52.2^{abc}
		700	83.8^{f}	83.2^{e}	78.5^{e}	20.2^{e}	45.4^{def}
	Roller mill	300	85.8^{de}	85.0^{d}	79.9^{e}	35.6^{cd}	46.9^{cde}
		500	86.0^{cde}	85.1^{d}	79.6^{e}	31.0^{d}	50.1^{bcd}
		700	83.0^{f}	81.1^{f}	71.9^{f}	3.4^{f}	40.3^{fgh}
110kg, BW	Hammermill	300	85.9^{cde}	86.0^{bcd}	87.1^{b}	32.8^{cd}	39.0^{gh}
		500	89.4^{a}	89.4^{a}	89.9^{a}	53.5^{a}	56.8^{a}
		700	84.0^{f}	83.1^{e}	83.6^{d}	15.4^{e}	36.9^{h}
	Roller mill	300	85.6^{e}	85.6^{cd}	84.2^{cd}	37.5^{cd}	38.4^{h}
		500	86.9^{bc}	86.4^{bc}	84.4^{cd}	34.9^{cd}	44.4^{efg}
		700	88.5^{a}	88.3^{a}	86.5^{bc}	40.9^{bc}	54.4^{ab}
Pooled SEM			0.4	0.4	0.9	3.0	2.0
Source of variance							
Period			<0.001	<0.001	<0.001	<0.001	0.010
Grinding method			0.338	0.031	<0.001	0.041	0.196
Particle size			<0.001	<0.001	<0.001	<0.001	<0.001
Period x grinding method			0.001	<0.001	0.004	<0.001	<0.001
Period x size			<0.001	<0.001	<0.001	<0.001	0.010
Grinding method x size			<0.001	<0.001	0.070	0.001	<0.001
Period x grinding method x size			<0.001	<0.001	<0.001	<0.001	<0.001

Table 14. Apparent total tract digestibility of DM, GE, CP, AEE and NDF of diets containing corn DDGS.

Item	Period 1. (55 kg, BW)			Period 2. (110 kg, BW)			SEM	*P*-value		
	HM 450	RM 450	NP 650	HM 450	RM 450	NP 650		Trt	Period	Trt x period
ATTD, %										
DM	79.8[ab]	79.2[bc]	77.9[c]	81.0[a]	80.7[ab]	77.8[c]	0.7	<0.001	0.091	0.435
GE	78.2[bc]	77.7[cd]	76.4[cd]	80.1[a]	79.9[ab]	76.0[d]	0.6	<0.001	0.026	0.115
CP	77.5[c]	77.0[c]	76.2[c]	81.5[ab]	81.7[a]	78.8[bc]	0.9	0.090	<0.001	0.494
AEE	46.2[a]	49.7[a]	38.2[b]	46.8[a]	48.7[a]	36.3[b]	2.4	<0.001	0.391	0.956
NDF	46.6	50.2	44.9	48.5	45.1	44.7	1.4	0.477	0.335	0.727

Table 15. Optimal particle size (microns) for each ingredient, growth period and milling method tested.

Ingredient	Growth stage	Grinding method	
		Roller mill	Hammer Mill
Corn	Grower	300	300-700
	Finisher	300	300-500
Wheat	Grower	300-500	300-500
	Finisher	700	500
Corn DDGS	Grower	450	
	Finisher	450	

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