RESEARCHREPORT
ANIMAL SCIENCE

Revised

Title: Effects of reducing the particle size of corn on the concentration of digestible and metabolizable energy and on the digestibility of energy, phosphorus, and amino acids by growing pigs -
NPB #: 11-170

Investigator: Hans H Stein

Institution: University of Illinois

Date Submitted: April 1, 2013

Industry Summary

The objective of this research was to measure the effects of different particle sizes of corn on energy and nutrient digestibility and to test the hypothesis that diets containing corn with reduced particle size can be formulated with less fat than diets containing corn ground to a greater particle size. Two digestibility experiments were conducted to determine effects of corn particle size on digestibility of energy, amino acids, and phosphorus in corn. Results of these experiments indicated that whereas the digestibility of amino acids and phosphorus is not influenced by the particle size of corn, the digestibility of energy is linearly increased if the particle size of corn is reduced from 865 to 339 microns. As a consequence of the greater digestibility of energy in corn ground to the smaller particle size, the concentration of metabolizable energy in corn ground to 339 microns is approximately 3.6% greater than if corn is ground to 865 microns (3,964 vs. 3,868 kcal ME per kg DM). Because of this increase in ME, it is possible to reduce the amount of added fat in diets containing corn ground to a smaller particle size compared with diets containing corn ground to a greater particle size without

changing the ME of the diet. Therefore, in the third experiment, diets that contained corn ground to 865, 677, 485, or 339 microns were formulated and fed to pigs from approximately 32 to 130 kg in a 3-phase feeding strategy. Within each phase, all diets were formulated to contain equal quantities of ME per kg, but diets formulated with the corn ground to 865 microns contained 1.60, 1.74, and 1.87% more soybean oil than diets containing corn ground to 339 microns for phase 1, phase 2, and phase 3, respectively. Results of this experiment indicated that final body weight, ADG, ADFI, G:F ratio, hot carcass weight, and dressing percentage were not different among pigs fed experimental diets. This observation confirms that the ME of corn ground to smaller particle size is indeed greater than if corn is ground to a greater particle size. The practical consequence of this is that less fat is needed in diets containing corn ground to a smaller particle size compared with diets containing corn ground to a greater particle size. Diets containing corn ground to the smaller particle size are, therefore, less expensive to produce than diets containing corn ground to a greater particle size, and the savings in feed cost will not have any impacts on pig growth performance or carcass composition. The net result, therefore, will be an increase in profits from pigs fed diets containing corn ground to a smaller particle size. Pork producers can take advantage of the results from this research by grinding corn to a reduced particle size.

For more information, please contact Dr. Hans H. Stein (email: hstein@illinois.edu)

Keywords: amino acid digestibility, corn, energy digestibility, growth performance, particle size, pigs

Scientific Abstract:

Three experiments were conducted to determine the concentration of DE and ME, the standardized total tract digestibility (STTD) of P, the standardized ileal digestibility (SID) of CP and AA, and the effect on growth performance and carcass characteristics of pigs fed corn ground to 4 different particle sizes (i.e., 339, 485, 677, and 865 µm). In Exp. 1, 40 growing barrows (initial BW 22.8 ± 2.1 kg) were placed in metabolism cages and allotted to a randomized complete block design with 4 diets and 10 replicate pigs per diet. One lot of corn was divided into 4 batches that were ground to the specified particle sizes and each batch was used in one diet that contained 97.7% corn (as-fed basis). Vitamins and minerals were included in the diets to meet the requirements for growing pigs with the exception that no inorganic P was used and all the P in the diets originated from corn. The concentration of ME was 3,964, 3,895, 3,868, and 3,826 kcal/kg DM for corn ground to a mean particle size of 339, 485, 677, and 865 µm, respectively. The ME concentration decreased (linear and quadratic, $P < 0.01$) as the particle increased. The STTD of P was 37.79, 37.12, 37.27, and 37.38% for corn ground to a mean particle size of 339, 485, 677, and 865 µm, respectively, and these values were not different. In Exp. 2, 10 growing barrows (initial BW: 29.2 ± 1.35 kg) were surgically equipped with a T-cannula in the distal ileum and randomly allotted to a replicated 5 × 5 Latin square design with 5 diets and 5 periods in each square. Four of the diets contained each batch of corn ground to a different particle size (96.55%, as-fed basis) as the only source of AA. A N-free diet was used to determine endogenous losses of CP and AA. With the exception of Trp, there was no impact of corn particle size on the SID of CP or any indispensable AA. In Exp 3, 36 gilts and 36 barrows (initial BW: 32.00 ± 1.58 kg) were allotted to 4 dietary treatments in a 3 phase program with phase 1 diets being offered from 32 to approximately 62 kg, phase 2 diets from approximately 62 to 94 kg, and phase 3 diets from approximately 92 to 130 kg. All diets were based on corn, soybean meal, and added soybean oil and the 4 dietary treatments were obtained by using corn ground to a mean particle size of 339, 485, 677, and 865 µm, respectively. Because of the increased ME in corn ground to the smaller particle size compared with the greater particle size, it was possible to reduce the amount of added fat in diets containing corn ground to a smaller particle size compared with diets containing corn ground to a greater particle size without changing the ME of the diet. Within each phase, all diets were formulated to contain equal quantities of ME per kg, but diets formulated with the corn ground to 865 microns contained 1.60, 1.74, and 1.87% more soybean oil than diets containing corn ground to 339 microns for phase 1, phase 2, and phase 3, respectively. Pigs were randomly allotted to the 4 dietary treatments in a 2 × 4 factorial design with sex (gilts and barrows) and diet as factors.

Each of the treatments contained 18 replications (9 gilts and 9 barrows). The final BW, ADFI, ADG, G:F ratio, hot carcass weight, and dressing percentage were not different among treatments. In conclusion, reduction of the particle size of corn from 865 to 339 µm linearly increased the concentration of ME in the corn, but the particle size of corn does not affect the STTD of P or the SID of indispensable AA and CP. As a consequence, by using corn ground to a smaller particle size, the amount of fat can be reduced in the diets without affected animal growth performance or carcass composition, which will reduce the cost of formulating diets containing corn ground to a smaller particle size.

Introduction:

The cost of feed has a high impact on the total production costs of pork meat. Therefore, maximizing the utilization of nutrients that are provided from the feed by the pig is one of the strategies to reduce the impact of feed costs on total costs of production. Grinding is used to reduce the particle size of feedstuffs and increase energy and nutrient digestibility (Wondra et al., 1995a; Laurinen et al., 2000; Mavromichalis et al., 2000; Kim et al., 2002) and it is accomplished with the use of either roller mills, hammer mills, or a combination of roller and hammer mills. It is currently recommended that corn grain be milled to an average particle size of approximately 640 - 650 µm (Wondra et al., 1995c; Kim et al., 2002), but it has also been documented that the digestibility of energy, DM, and N in corn fed to finishing pigs or sows increases as the particle size of the grain is reduced (Healy et al., 1994; Wondra et al., 1995a-d). However, there are no data that demonstrate the effects of particle size on the standardized ileal digestibility (**SID**) of AA and the standardized total tract digestibility (**STTD)** of P in corn grain, but it was reported that there is a tendency for an increase in the SID of AA in soybean meal as particle size is reduced (Fastinger and Mahan, 2003). It was also reported that there is no effect of particle size in distillers dried grain with solubles on the apparent total tract digestibility (**ATTD**) of P (Liu et al., 2012). The increased digestibility of energy that is a result of a reduced particle size of corn (Wondra et al., 1995c) results in an increase in the ME of the corn grain (Wondra et al., 1995d). The practical consequence of this increased ME is an improved G:F ratio for pigs fed diets that contain finely ground corn rather than coarsely ground corn (Healy et al., 1994; Wondra et al., 1995b).

The objectives of these experiments were to determine the concentration of DE and ME, the STTD of P, and the SID of AA and CP in corn grain that was ground to different particle sizes and fed to growing pigs. The hypothesis that there is a linear increase in the concentration of DE and ME and the digestibility of AA and P in corn, as particle size is reduced was tested. The second hypothesis was that diets containing corn ground to a smaller particle size can be formulated with less added fat without changing the concentration of ME in the diets.

Objectives

It was the objective of the current work to measure the effects of different particle sizes of corn on energy and nutrient digestibility and performance of growing pigs.

Materials and Methods:

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocols for these experiments. Pigs used in the 3 experiments were the offspring of G-performer boars mated to F-25 gilts (Genetiporc, Alexandria, MN). The same batch of corn (Pioneer P0528) was used in all diets in all 3 experiments and the corn was grown in Iowa in 2011. The corn grain was first rolled using an automatic Model CSU 500, 2 stage roller mill. The rolled grain was then divided into 4 batches that were ground using a Hammer Mill Bliss (Model #EL-9506-TF) 3, 10, 24 or 40 mm screens to obtain final particle sizes of 339, 485, 677, and 865 µm, respectively. The grain was milled at the Pioneer Hi-Bred Feed Mill in Johnston, IA, and stored at 15ºC until used.

Exp. 1: Energy and P Digestibility

Diets, Animals, and Experimental Design. Experiment 1 was designed to determine the concentration of DE and ME, the ATTD of GE, and the ATTD and STTD of P in the 4 batches of corn ground to different particle sizes (Table 1). Forty barrows (initial BW 22.8 ± 2.13 kg) were allotted to a randomized complete block design with 4 diets and 10 replicate pigs per diet and placed in metabolism cages that were equipped with a feeder and a nipple drinker, fully slatted floors, a screen floor, and urine trays. This allowed for the total, but separate, collection of urine and fecal materials from each pig.

Four corn-based diets that contained 97.7% corn were formulated (Tables 2 and 3). Vitamins and minerals were included in the diets to meet the requirement for growing pigs (NRC, 2012) with the exception that no inorganic P was used and all the P in the diets originated from corn. The 4 diets were similar with the exception that the corn used in each diet was ground to a different mean particle size (i.e., 339, 485, 677, and 865 µm).

Feeding and Sample Collection. The quantity of feed provided per pig daily was calculated as 3 times the estimated requirement for maintenance energy (i.e., 106 kcal ME per kg $^{0.75}$; NRC, 1998) for the smallest pig in each replicate and divided into 2 equal meals that were fed at 0800 and 1700 h. Water was available at all times. Individual pig BW was recorded at the beginning and at the end of the experiment and the amount of feed supplied each day was also recorded.

The experimental diets were fed to pigs for 12 d. The initial 5 d were considered an adaptation period to the diet, while urine and fecal samples were collected during the following 5 d according to standard procedures using the marker to marker approach (Adeola, 2001). Feces were collecting twice daily and stored at -20ºC immediately after collection. Urine buckets were placed under the metabolism cages to permit total collection. Buckets were emptied in the morning and afternoon and a preservative of 50 mL of 6*N* HCL was added to each bucket when they were emptied. The collected urine was weighed and a 20% subsample was stored at -20ºC.

Sample Analysis. At the conclusion of the experiment, urine samples were thawed and mixed, and a subsample was collected for analysis. Fecal samples were dried at 65ºC in a forced-air oven and ground through a 1-mm screen in a Wiley mill (model 4; Thomas Scientific, Swedesboro, NJ) before analyses. Urine samples were prepared and lyophilized before energy analysis as previously described (Kim et al., 2009a). All samples were analyzed in duplicate. Diets and ingredients were analyzed for CP by combustion (Method 999.03; AOAC Int., 2007) using a Rapid N cube apparatus (Elementar Americas Inc, Mt. Laurel, NJ), ash (Method 975.03; AOAC Int., 2007), for AA [Method 982.30 E (a, b, c); AOAC Int., 2007], ADF (Method 973.18; AOAC Int., 2007), and NDF (Holst, 1973). Ingredients were also analyzed for acid hydrolyzed ether extract (**AEE**), which was determined by acid hydrolysis using 3*N* HCl (Sanderson, 1986) followed by crude fat extraction with petroleum ether (Method 2003.06, AOAC Int., 2007) on a Soxtec 2050 automated analyzer (FOSS North America, Eden Prairie, MN). Diets, ingredients, feces, and urine samples were analyzed for GE using adiabatic bomb calorimetry (Model 6300, Parr Instruments, Moline, IL). Diets, ingredients, and fecal samples were also analyzed for DM (Method 930.15; AOAC Int., 2007), and for P and Ca by inductively coupled plasma spectroscopy (Method 975.03; AOAC Int., 2007) after wet ash sample preparation (Method 975.03; AOAC Int., 2007).

Calculations and Statistical Analysis. Particle size distribution and mean particle size of the corn grains were determined using 100 g of grain that was placed on the top of the test sieves (U.S sieve # 4, 6, 8, 12, 16, 20, 30, 40, 50, 70, 100, 140, 200, 270, and a solid metal pan), which were stacked from the biggest to the smallest aperture size. Thus, the test sieves were located in a vibratory sieve shaker for 10 min. The feedstuff material in each of the test sieves was recorded and weighed for further calculations of particle size distribution and mean particle size. After determination of the mean particle size as described by ANSI/ASAE, (2008), the surface area was calculated using mean particle size of the grain as a reference. The amount of energy lost in the feces and the amount of energy lost in the urine were calculated as well, and the quantities of DE and ME in each of the 4 diets were calculated (Widmer et al., 2007). The DE and ME in corn included in each diet was then calculated by dividing the DE and ME values for the corn diet by the inclusion rate of corn in the diet. The amount of P in the feces was subtracted from the P in the diet and the ATTD of P was calculated (Widmer et al.,

2007) and by correcting the ATTD of P by the average value for the basal endogenous loss of P (200 mg/kg DMI) values for STTD of P was calculated (Stein, 2011).

Data were analyzed by ANOVA using the Proc Mixed Procedure of SAS (SAS Institute Inc., Cary, NC). Homogeneity of the variances among treatments was confirmed using the UNIVARIATE procedure and this procedure was also used to identify outliers, but no outliers were detected. Diet was considered the fixed effect and replicate was the random effect. The Least Significant Means statement was used to calculate treatment means and the PDIFF option was used to separate means if differences were detected. The effect of decreasing particle size of corn was analyzed by orthogonal polynomial contrast. The coefficients for unequally spaced particle sizes of corn were obtained using the interactive matrix language procedure in SAS. The pig was the experimental unit for all analyses and an alpha level of 0.05 was used to assess significance among means.

Exp. 2: AA Digestibility

Diets, Animals, and Experimental Design. Experiment 2 was designed to determine the AID and the SID of CP and AA in the 4 batches of corn ground to different particle sizes. Ten growing barrows (initial BW: 29.2 ± 1.35 kg) were equipped with a T-cannula in the distal ileum according to procedures adapted from Stein et al. (1998). Pigs were allotted to a replicated 5 × 5 Latin square design with 5 diets and 5 periods in each square. Pigs were housed in individual pens (1.2 × 1.5 m) in an environmentally controlled room. A feeder and a nipple drinker were installed in each pen.

Five diets were formulated (Tables 4 and 5). Four of the diets each contained one of the 4 batches of corn (96.55%, as-fed basis) as the only AA-containing ingredient. The last diet was a N-free diet that was used to measure basal endogenous losses of AA and CP. Chromic oxide (0.4%) was included in all diets as an indigestible marker and vitamins and minerals were included in all diets to meet or exceed current requirement estimates (NRC, 2012).

Feeding and Sample Collection. All pigs were fed at a level of 3 times the maintenance energy requirement (i.e., 106 kcal ME per kg $^{0.75}$; NRC, 1998). The daily allotment of feed was divided into 2 equal meals that were provided at 0700 and 1700 h. Water was available at all times throughout the experiment. Pig weights were recorded at the beginning and at the end of each period and the amount of feed supplied each day was recorded. The initial 5 d of each period was considered an adaptation period to the diet. During the adaptation period, 50 g of an AA mixture (Table 6) was provided at each meal in addition to the allotted quantity of the experimental diet. The reason for adding the AA mixture was to reduce the effects of feeding diets that did not meet the pig's requirement for all AA (Pedersen et al., 2007). Ileal digesta were collected for 8 h on d 6 and 7. A 225-mL plastic bag was attached to the cannula barrel by a zip tie, and digesta that flowed into the bag were collected. Bags were removed whenever they were filled with digesta, or at least once every 30 min. They were then stored at -20ºC to prevent bacterial degradation of AA in the digesta.

Sample Analysis. At the conclusion of the experiment, ileal samples were thawed, mixed within animal and diet, and a subsample was collected for chemical analysis. Ileal digesta samples were lyophilized and finely ground prior to chemical analysis. All samples of digesta and diets were analyzed for DM, CP, and AA as described for Exp. 1, and for chromium concentrations of diets and ileal digesta were determine after nitric acid-perchloric acid wet ash sample preparation (Method 990.08, AOAC Int., 2007). All diet samples were also analyzed for ADF, NDF, ash, AEE, and GE as described for Exp. 1.

Calculations and Statistical Analysis. Values for AID, basal endogenous losses, and SID of CP and AA in the diets were calculated (Stein et al., 2007). Data were analyzed by ANOVA using the MIXED procedure (SAS Institute Inc., Cary, NC) as described for Exp. 1. Outliers were determined as values that deviated from the treatment mean by more than 1.5 times the interquantile range (Devore and Peck, 1993). One outlier was detected and removed from the data set (the outlier was from a pig fed the diet containing corn ground to a mean particle size 865 μm).

Exp. 3: Growth Performance

Diets, Animals, housing, and Experimental Design. Ground corn from the same batch as the corn used in Exp. 1 and 2 were used in this experiment and the corn had been stored at 10ºC from the time of grinding and until diets were mixed. The soybean meal that was used was sourced locally (Solae, Gibson City, IL) and this batch of soybean meal was used in all diets.

A total of 36 gilts and 36 barrows with an average initial BW of 32.00 ± 1.58 kg were used. All pigs were housed individually in pens (0.9 × 1.8 m) with fully slatted concrete floors. A feeder and a nipple drinker were provided in each pen. Feed and water were provided on an ad libitum basis throughout the experiment. Pigs were fed a 3 phase program (Table 8) with phase 1 diets being offered from approximately 32 to 62 kg, phase 2 diets from approximately 62 to 94 kg, and phase 3 diets from approximately 94 to 130 kg. Within each phase, 4 corn-soybean meal based diets were formulated to meet or exceed current nutrient requirements (NRC, 2012). The only difference among diets within each phase was that the corn that was used was ground to a different particle size (i.e., 339, 485, 677, and 865 µm) and addition of soybean oil was adjusted to compensate for the reduction of ME as particle size of corn increased. Thus all diets within each phase were formulated to contain the same amount of ME. Pigs were randomly allotted to 4 dietary treatments in a 2 × 4 factorial design with sex (gilts and barrows) and diet as factors. Each of the treatments contained 18 replications (9 gilts and 9 barrows).

Feeding and Growth performance. The 72 pigs that were used in this experiment were divided into 2 groups of 36 pigs (18 gilts and 18 barrows). The 2 groups were allotted to treatment diets with a 1-wk interval and pigs in each group were harvested 1 wk apart to maintain the same number of days on feed for all pigs. Individual pig BW was recorded at the start of the experiment, on d 29, 58, and at the conclusion of the experiment (d 93). Daily feed allotments were recorded as well and feed left in the feeders was recorded on the same days as pigs were weighted. At the conclusion of the experiment, data were summarized to calculate ADG, ADFI, and G:F for each pig and summarized within each phase and overall for each sex and diet.

Sample Collection, Slaughter, and Carcass Evaluation. On the last day of the experiment, feed was removed from the feeders and the final BW of each pig was recorded. After an overnight fast, pigs were transported to the Meat Science Laboratory at the University of Illinois (Urbana, IL). Pigs were kept in the holding pens at the Meat Science Laboratory for 0 to 3 h before they were slaughtered. They were allowed free access to water during this time. The live BW of each pig was recorded just prior to slaughter. Pigs were killed by electrical stunning, lifted off the floor, and exsanguinated. After reflex action had ended, pigs were scalded and washed. Carcasses were dehaired and eviscerated, and the hot carcass weight (**HCW**) was then recorded and carcasses were chilled for 24h. At 24h post-mortem, the pH of the longissimus dorsi (**LD**) was measured at the 10th rib by a handheld pH star probe fitted with a glass electrode (SFK Technologies Inc., Cedar Rapids, IA; 2-pint calibration; pH 4 and 7). Backfat was measured perpendicular to the skin at the ¾ point of the loin eye area (**LEA**) at the 10th (NPPC, 1991). Loin eye area was measured by tracing the face of LD on double-matted acetate paper. Loin tracing were traced in duplicate using a Super Planix α polar planimeter (Tamaya Technics Inc., Tokyo, Japan), and the average of the 2 measurements was reported as LEA for each carcass. The digestive tract was flushed with water to remove digesta, and liver, heart, kidney, spleen, stomach, and the intestines were patted dry and weighed.

Freshly voided feces were collected on the last day of the experiment in the morning and pH of the fecal samples was immediately measured using a pH meter (Accumet Basic, Fisher Scientific, Pittsburgh, PA). Likewise, the pH of the stomach, ileal, and cecum content were measured on the day of slaughter. Cecum content samples (20 g) were mixed with 2*N* HCl in a 1:1 ration and the samples were stored at -20ºC until de concentrations of short-chain fatty acids (**SCFA**) were analyzed.

Chemical Analysis. Diets were analyzed for GE as described for Exp. 1. The concentration of SCFA in the cecum samples was measured using the cecum sample that was preserved in HCl. Preparation of the cecum sample for SCFA and LCFA analysis was as described by Urriola and Stein (2010) except that 2 mL of the cecum:HCl mixture was mixed with 8 mL of distilled water. The procedures for SCFA were described by Erwin et al. (1961) and by Urriola and Stein (2010).

Results:

The particle size distribution of corn in each of the sieve used is shown in Figure 1.

Exp. 1: Energy and P Digestibility

There were no differences in GE intake, or in fecal and urine excretion of GE among pigs fed the 4 diets (Table 8). However, the ATTD of GE was reduced (linear and quadratic, $P < 0.01$) as the particle size increased from 339 to 865 μm, respectively. The concentration of DE (as-fed and on a DM basis) decreased (linear and quadratic, $P < 0.05$) as the particle increased from 339 to 865 μm. Likewise, the ME concentration calculated on an as-fed and on a DM basis decreased from 3,432 to 3,311 kcal/kg and from 3,964 to 3,826 kcal/kg, respectively, when corn particle size increased from 339 to 865 μm.

There were no differences in ADFI and P intake among pigs fed the 4 experimental diets (Table 9). The concentration of P in feces decreased linearly ($P < 0.01$) as corn particle size increased from 339 to 865 μm. However, there were no differences in P output and absorbed P among diets. Likewise, the ATTD and STTD of P did not increased (linear, $P > 0.05$) as particle size of corn decreased from 865 to 339 μm

Exp. 2: AA Digestibility

There were no differences in the AID of CP and all indispensable AA among diets (Table 10), except for the AID of Trp, which was reduced at the greatest particle size (quadratic $P < 0.01$). The average AID of indispensable AA was also not different among treatments. Likewise, the AID of all dispensable AA was not different among diets, except that the AID of Gly decreased (linear, $P < 0.01$) as particle size of corn increased.

The SID of CP and all indispensable, and dispensable AA did not increase (linear, $P > 0.05$) as particle size of corn decreased from 865 to 339 μm (Table 11). The average SID of indispensable AA was also not different, but the average SID of dispensable AA decreased linearly ($P < 0.05$) as particle size of corn increased.

Exp. 3: Growth Performance

There were no differences in the starting weight or in final weight among treatments (Table 12). Likewise, no differences among treatments were observed for ADG, ADFI, or G:F. This was true for the entire experimental period as well as for each of the 3 phases. There was, however, a tendency ($P = 0.06$) for an improved dressing percentage for pigs fed the diet with corn ground to the least particle size compared with pigs fed the diet with corn ground to the greatest particle size (Table 13). The main reason for this increase was that the intestinal weight was less ($P < 0.05$) for pigs fed the diet with the least particle size compared with pigs fed the other diets. However, no differences in the weights of other organs were observed among treatments. Likewise, no differences in back fat thickness, loin eye area, or fat free lean percentage, or loin pH were observed.

The pH of contents in the stomach and the ileum were not affected by treatments, but pH in contents of the cecum and the colon was less ($P < 0.05$) for pigs fed diets containing corn ground to the 2 greater particle sizes compared with pigs fed diets containing corn ground to the least particle sizes (Table 14). In contrast, pigs fed diets containing corn ground to 865 μm had greater ($P < 0.05$) concentrations of acetate and propionate in cecal contents compared with pigs fed diets containing corn ground to 485 or 339 μm, but pigs fed the diets containing corn ground to 339 μm had less ($P < 0.05$) acetate and propionate in cecal contents than pigs fed diets containing corn ground to 677 or 865 μm. Pigs fed diets ground to 677 or 865 μm also had greater ($P < 0.05$) concentrations of butyrate in cecal contents than pigs fed diets containing corn ground to 485 or 339 μm, but pigs fed diets containing corn ground to 339 microns had less ($P < 0.05$) butyrate in cecal contents than pigs fed all other diets. However, the concentration of isobuterate in the cecal contents increased ($P = 0.05$) as the particle size was reduced, whereas no differences among treatments were observed for isovalerate and valerate.

Discussion:

The concentration of GE, CP, DM, P, Ca, EAA, and AA in the corn used in this experiment is in agreement with values reported by Pedersen et al. (2007), Soares et al. (2011), and NRC (2012). Cereal grains and pulse crops are usually ground before being included in diets fed to pigs. Both roller mills and hammer mills can be used to grind cereal grains and the choice between them is often based on the grinding capacity needed, electricity efficiency, and type of feedstuffs used (Hancock and Behnke, 2001). A roller mill is more energy efficient than a hammer mill but roller mills can usually not grind corn to particle sizes of less than approximately 600 μm, whereas hammer mills can grind corn to approximately 300 μm. By first rolling and then grinding the grain, we attempted to eliminate the effect of mill type on the digestibility values. In previous experiments in which particle sizes of corn has been evaluated, the greatest particle size was achieved using a roller mill, whereas the smaller particle sizes were obtained using a hammer mill (Wondra et al., 1994a,d).

The increase in standard deviation and reduction in surface area that was observed as particle size increased is in agreement with values reported by Wondra et al. (1994a).

Exp. 1: Energy and P Digestibility

The concentration of GE, DE, and ME in corn concurs with reported values (Widmer et al., 2007; NRC, 2012) and the ATTD of GE was also in good agreement with values reported by Baker and Stein (2009) and Petersen et al. (2007). The DE:ME ratio obtained for all particle sizes is also within the range of reported values (Widmer et al., 2007; NRC, 2012). The increase in DE and ME that was observed as the particle size was reduced is less than the increase reported by Wondra et al. (1994d), when grain with different particle sizes were fed to sows, but quite similar to the increase reported by Oryschak et al. (2002). The reason for this difference is most likely that sows have a greater ability to ferment fiber and nutrients compared with growing pigs (Noblet and Shi, 1993). The observation that there is no differences in GE excreted in the urine amount treatments, indicates that the entire improvement of ME in corn due to a reduced particle size is an increase in energy digestibility. It is likely that the improvement in digestibility is a result of an increased contact between endogenous enzymes or intestinal microbes and corn particles due to the increase surface area of the grain with the reduced particle size (Kim et al., 2000; Medel et al., 2000). However, the fact that there is no effect of particle size on P digestibility indicates that P digestibility in coarse grain is not limited by access for enzymes. The majority of the digestible carbohydrates in corn is starch, which primarily is digested by pancreatic alpha amylase. If it is assumed that alpha amylase is as efficient in digesting starch in coarsely ground grain as the intestinal phosphatases are, then it may be speculated that the improvement in the digestibility of GE that was observed as the particle size was reduced primarily is a result of increased fermentation of the fiber in corn. Thus, it appears that course grinding of corn may restrict the access of microbes to the fermentable material in the grain, where it appears that the effect of the digestive enzymes is not reduced by course grinding.

An improvement in the concentration of DE and the ATTD of GE of a magnitude similar to what was observed in this experiment was reported for pigs fed a barley-field pea diet with a particle size of 400 µm compared with pigs fed the same diet ground to 700 µm (Oryschak et al. (2002). Likewise, the ATTD of GE and the concentration of DE and ME, increased when pigs were fed distiller dried grains with solubles (**DDGS**) ground to 308 µm compared with pigs fed DDGS ground to 818 µm (Liu et al., 2012). In contrast, if the particle size of lupins is decreased from 1304 to 567 µm, the ATTD of energy is not affected (Kim et al., 2009b). It is not clear why this difference among feed ingredients exists.

The STTD of P in corn that was calculated in this experiment is in agreement with values reported by Li et al. (2013) and NRC (2012). The observation that particle size did not affect the ATTD or STTD of P in corn of corn concurs with observations by Liu et al. (2012), who reported that reduction of particle size in DDGS did not influence the ATTD of P. In contrast, the ATTD of P in a barley-field pea diet ground to 400 µm is slightly greater than if the same diet is ground to 850 µm (Oryschak et al., 2002).

Exp. 2: AA Digestibility

The AID and SID of AA in corn obtained in this experiment are within the range of reported values (Bohlke et al., 2005; NRC, 2012). The fact that particle size of corn did not influence the AID and SID of AA concurs with observations by Fastinger and Mahan (2003) who reported that a reduction of particle size of SBM from 949 to 185 µm has no effect on the SID of indispensable AA. In contrast, the SID of AA in lupins increases as particle size decreases (Kim et al., 2009b).

Although reduction of particle size of feedstuffs often results in increased energy or nutrient digestibility, differences among ingredients exist. There may also be disadvantages of fine grinding compared with coarse grind. For instance, the electricity used to process feedstuffs is an important component in a feel mill's budget. Corn milled at 600 µm rather than 1000 µm with a hammer mill increased energy usage and when particle size was decreased from 1,000 to 400 µm, the energy usage increased almost 2.5 times (Wondra et al., 1995c). The production rate (ton/h) also decreases and electricity required to mill the grain increase as particle size is reduced (Healy et al., 1994). Likewise, it has been hypothesized that reduced particle size may result in poor flowability of diets (Appel, 1994). This concurs with observations by Liu et al. (2012) who reported that as particle size of DDGS is reduced from 818 to 308 µm, the flowability of the diet is reduced. In addition, pigs fed ingredients with a reduced particle size may develop gastric ulcers (Mahan et al., 1966; Maxwell et al., 1970; Wondra et al., 1995b) and development of ulcers is considered one of the major reasons for economical losses in the U.S. swine industry (Friendship, 2003).

Exp. 3: Growth Performance

The observation that no differences in growth performance among treatments were observed confirms that the differences in ME among the 4 batches of corn that were calculated from Exp. 1 were correct and there were no indications that there were any differences among diets in ME despite the differences in inclusion of soybean oil in the diets. Based on this, it is concluded that diets with the least particle sizes were the least expensive to produce and the savings from added fat resulted in reduced diet costs and increased profits from production. We are not aware of any other experiments that have been conducted to indicate the amount of fat that can be spared by reducing the particle size of corn. The fact that dressing percentage increased as corn was ground to a finer particle size will further contribute to an increase in profits for these pigs.

The reduction in pH of cecal and colon contents that were observed for pigs fed the corn with the least particle size indicates that less VFA were produced by these pigs compared with pigs fed the diets containing corn ground to a greater particle size. This assumption is supported by the measured VFA in the cecal contents. It is, therefore, likely that less fermentation took place in the hindgut of pigs fed the diets containing corn ground to 339 or 485 µm compared with corn ground to the greater particle sizes. The reason for the reduced fermentation in pigs fed corn ground to the smaller particle sizes may be that more of the starch and possibly the fiber were absorbed in the small intestine of these pigs, which in turn would result in reduced substrate for the microbes for fermentation in the hindgut. This also explains the increased ME of the grain ground to the smaller particle size. To our knowledge, there has been no previous reports on the effects of corn particle size on pH or VFA concentrations in intestinal contents of pigs, but based on this research it is hypothesized that reduced particle size results in improved digestion and absorption of nutrients in the small intestine, and in reduced fermentation in the hindgut.

Conclusions:

Reducing the particle size of corn from 865 to 339 µm linearly increased the ATTD of GE and the concentration of DE and ME in corn. However, there were no effects of corn particle size on the STTD of P or the SID of indispensable AA and CP. The increased concentration of ME in finely ground corn makes it possible to reduce the inclusion of added lipids in diets containing finely ground corn, which will result in reduced diet costs and improved profits. Results of the growth performance experiment confirmed this hypothesis and also indicated that the dressing percentage is improved if diets contain corn ground to a reduced particle size. The reason for the increased ME of finely ground corn is likely that more nutrients are absorbed in the small intestine and less fermentation take place in the large intestine.

Literature Cited

Adeola, O. 2001. Digestion and balance techniques in pigs. Pages 903-916 in Swine Nutrition. 2nd ed. A. J. Lewis and L. L. Southern, ed. CRC Press, Washington, DC.

ANSI/ASAE. 2008. Method of determining and expressing fineness of feed materials by sieving. ANSI/ASAE Standard ANSI/ASAE S319.4.

Appel, W. B. 1994. Physical properties of feed ingredients. Pages 151–152 in Feed Manufacturing Technology. 4th ed. Am. Feed Industry Assoc., Inc., Arlington, VA.

AOAC International. 2007. Official Methods of Analysis of AOAC Int. 18th ed. Rev. 2. W. Hortwitz and G. W. Latimer Jr., ed. AOAC Int., Gaithersburg, MD.

Baker, K. M., and H. H. Stein. 2009. Amino acid digestibility and concentration of digestible and metabolizable energy in soybean meal produced from conventional, high-protein, or low-oligosaccharide varieties of soybeans and fed to growing pigs. J. Anim. Sci. 87: 2282-2290.

Bohlke, R. A., R. C. Thaler, and H. H. Stein. 2005. Calcium, phosphorus, and amino acid digestibility in low-phytate corn, normal corn, and soybean meal by growing pigs. J. Anim. Sci. 83:2396-2403.

Devore, J., and R. Peck. 1993. Statistics: The Exploration and Analysis of Data. 2end ed. Duxbury Press, Belmont, CA.

Erwin, E. S., G. J. Marco, and E. M. Emery. 1961. Volatile fatty acids analysis of blood and rumen fluid by gas chromatography. J. Dairy Sci. 44:1768-1771.

Fastinger, N. D., and D. C. Mahan. 2003. Effect of soybean meal particle size on amino acid and energy digestibility in grower-finisher swine. J. Anim. Sci. 81:697-704.

Friendship, R. M. 2003. Gastric ulcers: an under-recognized cause of mortality and morbidity. Advances in Pork Production. 14:159-164.

Hancock, J. D., and K. C. Behnke. 2001. Use of ingredient and diet processing technologies (Grinding, Mixing, Pelleting, and Extruding) to produce quality feeds for pigs. Pages 474-63 in Swine Nutrition. 2nd ed. A. J. Lewis and L. L. Southern, ed. CRC Press, Washington, DC.

Healy, J. D., Hancock, G. A. Kennedy, P. J. Bramel-cox, K. C. Behnke, and R. H. Hines. 1994. Optimum particle size of corn and hard and soft sorghum for nursery pigs. J. Anim. Sci. 72:2227-2236.

Holst, D. O. 1973. Holst filtration apparatus for Van Soest detergent fiber analysis. J. AOAC. 56:1352-1356.

Kim, I. H., H. Cao, J. D. Hancock, and D. F. Li. 2000. Effects of processing and genetics on nutritional value of sorghum in chicks and pigs. Asian-Aust. J. Anim. Sci. 13:1337-1344.

Kim, B. K., G. I. Petersen, R. B. Hinson, G. L. Allee, and H. H. Stein. 2009a. Amino acid digestibility and energy concentration in a novel source of high-protein distillers dried grains and their effects on growth performance of pigs. J. Anim. Sci. 87:4013-4021.

Kim, J. C., B. P. Mullan, J. M. Heo, C. F. Hansen, and J. R. Pluske. 2009b. Decreasing dietary particle size of lupins increases apparent ileal amino acid digestibility and alters fermentation characteristics in the gastrointestinal tract of pigs. Br. J. Nutr. 102:350-360.

Kim, I. H., J. D. Hancock, J. W. Hong, M. R. Cabrera. R. H. Hines, and K. C. Behnke. 2002. Corn particle size affects nutritional value of simple and complex diets for nursery pigs and broiler chicks. Asian-Aust. J. Anim. Sci. 15:872-877.

Laurinen, P. H., Siljander-Rasi, J. Karhunen, T. Alaviuhkola, M. Nasi, and K. Tuppi. 2000. Effects of different grinding methods and particle size of barley and wheat on pig performance and digestibility. Anim. Feed Sci. Technol. 83:1-16.

Li, S. F., Y. B. Niu, J. S. Liu, L. Lu, L. Y. Zhang, C. Y. Ran, M. S. Feng, B. Du, J. L. Deng, and X. G. Luo. 2013. Energy, amino acid, and phosphorus digestibility of phytase transgenic corn for growing pigs. J. Amin. Sci. 91:298-308.

Liu, P., L. W. O. Souza, S. K. Baidoo, and G. C. Shurson. 2012. Impact of DDGS particle size on nutrients digestibility, DE and ME content, and flowability in diets for growing pigs. J. Anim. Sci. 90: 4925-4932.

Mahan, D. C., R. A. Pickett, T. W. Perry, T. M. Curtim, W. R. Featherston, and W. M. Beeson. 1966. Influence of various nutritional factors and physical form of feed on esophagogastric ulcers in swine. J. Anim. Sci. 25:1019-1023.

Mavromichalis, I., J. D. Hancock, B. W. Sense, T. L. Gugle, G. A. Kennedy, R. H. Hines, and C. L. Wyatt. 2000. Enzyme supplementation and particle size of wheat in diets for nursery and finishing pigs. J. Anim. Sci. 78:3086-3095.

Maxwell, C. V., E. M. Reimann, W. G. Hoekstra, T. Kowalczyk, N. J. Benevenga, and R. H. Grummer. 1970. Effect of dietary particle size on lesion development and on the contents of various regions of the swine stomach. J. Anim. Sci. 30:911-922.

Medel, P., M. Garcia, R. Lazaro, C. de Blas, and G. G. Mateos. 2000. Particle size and heat treatment of barley in diets for early-weaned piglets. Anim. Feed Sci. Technol. 84:13-21.

Noblet, J., and X. S. Shi. 1993. Comparative digestibility of energy and nutrients in growing pigs fed ad libitum and adult sows fed at maintenance. Livest. Prod. Sci. 34:137-152.

NRC. 1998. Nutrient requirements of swine. 10th rev. ed. Natl. Acad. Press, Washington, DC.

NRC. 2012. Nutrient requirements of swine. 11th rev. ed. Natl. Acad. Press, Washington, DC.

NPPC. 1991. Procedures to Evaluate Market Hogs. Natl. Pork Prod. Council, Des Moines, IA.

NPPC. 1999. Pork Quality Standards. Natl. Pork Prod. Council, Des Moines, IA.

Oryschak, M. A., P. H. Simmins, and R. T. Zijlstra. 2002. Effect of dietary particle size and carbohydrase and/or phytase supplementation on nitrogen and phosphorus excretion of grower pigs. Can. J. Anim. Sci. 82, 533–540.

Pedersen, C., M. G. Boersma, and H. H. Stein. 2007. Energy and nutrients digestibility in NutriDense corn and other cereal grains fed to growing pigs. J. Anim. Sci. 85:2473:2483.

Sanderson, P. 1986. A new method of analysis of feeding stuffs for the determination of crude oils and fats. Pages 77-81 in Recent Advances in Animal Nutrition. W. Haresign and D. J. A. Cole, eds. Butterworths, London, U.K.

Soares, J. A., V. Singh, H. H. Stein, R. Srinavasan, and J. E. Pettigrew. Enhanced distillers dried grains with solubles (DDGS) has greater concentration of digestible and metabolizable energy than DDGS when fed to growing and finishing pigs. 2011. Can. J. Anim. Sci. 91:663-667.

Stein, H. H. 2011. Standardized total tract digestibility (STTD) of phosphorus. Pages 47–52 in Proc. Midwest Swine Nutr. Conf., Indianapolis, IN.

Stein, H. H., B. Sève, M. F. Fuller, P. J. Moughan, and C. F. M. de Lange. 2007. Invited review: Amino acid bioavailability and digestibility in pig feed ingredients: Terminology and application. J. Anim. Sci. 85:172-180.

Stein, H. H., C. F. Shipley, and R. A. Easter. 1998. Technical Note: A technique for inserting a T-cannula into the distal ileum of pregnant sows. J. Anim. Sci. 76:1433-1436.

Urriola, P. E., and H. H. Stein. 2010. Effects of distillers dried grains with solubles on amino acid, energy, and fiber digestibility and on hindgut fermentation of dietary fiber in a c corn-soybean meal diet fed to growing pigs.

Widmer, M. R., L. M. McGinnis, and H. H. Stein. 2007. Energy, amino acid, and phosphorus digestibility of high protein distillers dried grain and corn germ fed to growing pigs. J. Anim. Sci. 85:2994-3003.

Wondra, K. J., J. D. Hancock, G. A. Kennedy, R. H. Hines, and K. C. Behnke. 1995a. Reducing particle size of corn in lactation diets from 1,200 to 400 micrometers improves sow and litter performance. J. Anim. Sci. 73:421-426.

Wondra, K. J., J. D. Hancock, K. C. Behnke, R. H. Hines, and C. R. Stark. 1995b. Effects of particle size and pelleting on growth performance, nutrient digestibility, and stomach morphology in finishing pigs. J. Anim. Sci. 73:757-763.

Wondra, K. J., J. D. Hancock, K. C. Behnke, and C. R. Stark. 1995c. Effects of mill type and particle size uniformity on growth performance, nutrient digestibility, and stomach morphology in finishing pigs. J. Anim. Sci. 73:2564-2573.

Wondra, K. J., J. D. Hancock, G. A. Kennedy, K. C. Behnke, and K. R. Wondra. 1995d. Effects of reducing particle size of corn in lactation diets on energy and nitrogen metabolism in second parity sows. J. Anim. Sci. 73:427-432.

Tables:

Table 1. Analyzed nutrient composition of corn with different particle sizes, as-fed basis

	Corn			
Item	339 μm	485 μm	677 μm	865 μm
GE, kcal/kg	3,870	3,851	3,900	3,942
DM, %	86.30	86.71	86.40	86.54
CP, %	7.00	7.25	7.23	7.08
Ash, %	1.10	1.23	1.39	1.15
AEE[1], %	3.57	3.53	3.51	3.45
NDF, %	9.25	9.29	10.01	11.06
ADF, %	1.91	2.24	2.27	2.41
P, %	0.29	0.30	0.34	0.31
Ca, %	0.03	0.03	0.03	0.03
Indispensable, AA %				
Arg	0.35	0.35	0.37	0.35
His	0.20	0.20	0.21	0.20
Ile	0.24	0.25	0.26	0.24
Leu	0.83	0.83	0.84	0.85
Lys	0.25	0.25	0.26	0.25
Met	0.14	0.13	0.14	0.14
Phe	0.35	0.35	0.35	0.35
Thr	0.25	0.25	0.24	0.25

Trp	0.05	0.05	0.05	0.06
Val	0.35	0.36	0.38	0.35
Dispensable, AA %				
Ala	0.51	0.51	0.52	0.51
Asp	0.49	0.49	0.50	0.49
Cys	0.15	0.14	0.15	0.15
Glu	1.26	1.26	1.25	1.28
Gly	0.30	0.30	0.30	0.30
Pro	0.63	0.64	0.62	0.64
Ser	0.31	0.30	0.30	0.32
Tyr	0.21	0.20	0.22	0.20
Total AA	6.87	6.86	6.96	6.93
Average, µm	339	485	677	865
Standard deviation	1.89	2.92	3.20	3.15
Surface area (cm^2)/gram	164.5	166.6	132.1	101.4

[1] AEE = acid hydrolyzed ether extract.

Table 2. Composition of experimental diets containing corn that was ground to different particle sizes, as-fed basis, Exp. 1

	Diet
Ingredients, %	Corn[1]
Ground corn	97.70
Ground limestone	1.60
Sodium chloride	0.40
Vitamin mineral premix[2]	0.30

Total	100.00

[1] Four diets that contained corn ground to a particle size of 339, 485, 677, or 865 μm were formulated.

[2] Provided the following quantities of vitamins and micro minerals per kilogram of complete diet: vitamin A as retinyl acetate, 11,128 IU; vitamin D_3 as cholecalciferol, 2,204 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.58 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin as nicotinamide and nicotinic acid, 44 mg; folic acid, 1.58 mg; biotin, 0.44 mg; Cu, 10 mg as copper sulfate; Fe, 125 mg as iron sulfate; I, 1.26 mg as potassium iodate; Mn, 60 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; and Zn, 100 mg as zinc oxide.

Table 3. Analyzed composition of experimental diets containing corn that was ground to different particle sizes, as-fed basis, Exp. 1

	Diet			
	339 μm	485 μm	677 μm	865 μm
GE, kcal/kg	3,783	3,776	3,736	3,799
DM, %	86.57	86.54	86.50	86.54
CP, %	6.77	6.97	6.85	6.85
Ash, %	2.90	2.60	2.86	2.54
P, %	0.28	0.26	0.28	0.31
Ca, %	0.61	0.66	0.75	0.51
NDF, %	7.53	8.14	9.26	10.41
ADF, %	1.79	1.80	1.98	2.30

Table 4. Composition of experimental diets containing corn that was ground to different particles sizes and in the N-free diet as-fed basis, Exp. 2

Ingredient, %	Diet Corn[1]	 N-free[2]
Ground corn	96.55	-
Sucrose	-	20.00
Cornstarch	-	67.60
Solka floc	-	4.00
Soybean oil	-	4.00
Ground limestone	0.85	0.20
Magnesium oxide	-	0.10
Potassium carbonate	-	0.40
Dicalcium phosphate	1.50	2.60
Sodium chloride	0.40	0.40
Chromic oxide	0.40	0.40
Vitamin mineral premix [3]	0.30	0.30
Total	100.00	100.00

[1] Four diets that contained corn ground to a particle size of 339, 485, 677, or 865 μm were formulated.

[2] N-free = nitrogen free diet.

[3] Provided the following quantities of vitamins and micro minerals per kilogram of complete diet: vitamin A as retinyl acetate, 11,128 IU; vitamin D_3 as cholecalciferol, 2,204 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin,

6.58 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin as nicotinamide and nicotinic acid, 44 mg; folic acid, 1.58 mg; biotin, 0.44 mg; Cu, 10 mg as copper sulfate; Fe, 125 mg as iron sulfate; I, 1.26 mg as potassium iodate; Mn, 60 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; and Zn, 100 mg as zinc oxide.

Table 5. Analyzed nutrient composition of experimental diets, as-fed basis, Exp. 2

	Diet[1]				
Item	339 μm	485 μm	677 μm	865 μm	N-free[1]
GE, kcal/kg	3,725	3,726	3,700	3,678	3,753
DM, %	86.59	86.58	86.59	86.72	90.87
CP, %	7.00	7.16	6.21	6.65	0.30
Ash, %	4.04	3.93	3.93	4.55	3.91
NDF, %	8.75	9.09	8.77	8.03	4.62
ADF, %	1.77	2.14	2.22	1.91	3.19
Indispensable, AA %					
Arg	0.34	0.33	0.30	0.33	0.01
His	0.19	0.19	0.18	0.19	0.00
Ile	0.23	0.24	0.22	0.24	0.01
Leu	0.82	0.81	0.78	0.80	0.03
Lys	0.24	0.23	0.22	0.23	0.01
Met	0.13	0.13	0.12	0.13	0.00
Phe	0.34	0.34	0.32	0.33	0.02
Thr	0.25	0.24	0.23	0.23	0.01
Trp	0.06	0.05	0.05	0.04	0.03

Val	0.34	0.34	0.32	0.35	0.00
Dispensable, AA %					
Ala	0.50	0.49	0.47	0.48	0.03
Asp	0.48	0.47	0.45	0.47	0.02
Cys	0.14	0.13	0.13	0.14	0.00
Glu	1.24	1.21	1.17	1.20	0.04
Gly	0.30	0.29	0.27	0.29	0.02
Pro	0.63	0.62	0.59	0.61	0.06
Ser	0.30	0.27	0.28	0.26	0.01
Tyr	0.21	0.20	0.18	0.19	0.01
Total AA	6.74	6.58	6.28	6.51	0.31

[1] N-free = nitrogen free diet.

Table 6. Composition of the AA mixture used in Exp. 2, as-fed basis[1]

AA	Inclusion, %
L-Gly	41.20
L-Lys-HCl	20.50
DL-Met	3.30
L-Thr	8.40
L-Trp	2.70
L-Ile	6.30
L-Val	7.40
L-His	3.70
L-Phe	6.50

Total	100.00

[1] The AA mixture was fed to the pigs used in Exp. 2 in the amount of 100 g per d for the initial 5 d of each period, but the mixture was not fed on d 6 and 7 when ileal digesta were collected.

Table 7. Composition of experimental diets, as-fed basis

	Diets											
	Phase 1				Phase 2				Phase 3			
Item	339 μm	485 μm	677 μm	865 μm	339 μm	485 μm	677 μm	865 μm	339 μm	485 μm	677 μm	865 μm
Ingredient, %												
Ground corn	67.76	67.14	67.17	66.07	73.22	72.52	72.61	71.47	78.22	77.45	77.57	76.34
Soybean meal, 48% CP	27.40	27.30	26.90	27.50	22.20	22.10	21.60	22.20	17.40	17.30	16.80	17.40
Soybean oil	2.00	2.78	3.12	3.60	2.00	2.85	3.23	3.74	2.00	2.92	3.30	3.87
Ground limestone	0.92	1.00	0.95	0.92	0.87	0.98	0.92	0.90	0.78	0.90	0.83	0.82
Dicalcium phosphate	0.92	0.77	0.87	0.90	0.74	0.57	0.68	0.71	0.64	0.45	0.55	0.60
L-lysine HCL	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
DL-methionine	0.10	0.11	0.10	0.10	0.07	0.08	0.07	0.07	0.05	0.07	0.05	0.06
L-threonine	0.05	0.05	0.04	0.06	0.05	0.05	0.04	0.06	0.06	0.06	0.05	0.07
Sodium chloride	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin-mineral premix[1]	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Analyzed composition												
GE, kcal/kg	4,075	4,077	4,113	4,308	4,035	4,087	4,125	4,086	4,012	4,102	4,088	4,114
Indispensable, AA %												
Arg	1.22	1.20	1.14	1.25	1.01	1.02	0.94	1.01	0.96	0.86	0.85	0.87
His	0.48	0.47	0.45	0.48	0.41	0.42	0.38	0.41	0.39	0.36	0.36	0.36
Ile	0.80	0.77	0.73	0.80	0.65	0.68	0.60	0.66	0.62	0.56	0.57	0.57
Leu	1.63	1.57	1.51	1.56	1.39	1.43	1.29	1.38	1.37	1.24	1.30	1.27
Lys	1.11	1.20	1.03	1.32	0.92	0.95	0.87	0.94	0.86	0.82	0.73	0.80
Met	0.36	0.42	0.34	0.35	0.29	0.29	0.27	0.31	0.29	0.30	0.28	0.27
Phe	0.92	0.90	0.86	0.91	0.77	0.78	0.70	0.77	0.73	0.66	0.67	0.67
Thr	0.72	0.68	0.67	0.71	0.62	0.60	0.57	0.60	0.62	0.54	0.57	0.56
Trp	0.24	0.21	0.21	0.24	0.19	0.19	0.18	0.19	0.18	0.18	0.17	0.16
Val	0.95	0.93	0.86	0.93	0.77	0.80	0.71	0.82	0.73	0.72	0.71	0.68
Dispensable, AA %												
Ala	0.94	0.92	0.87	0.91	0.81	0.83	0.77	0.81	0.80	0.74	0.75	0.74
Asp	1.86	1.82	1.71	1.87	1.49	1.53	1.39	1.51	1.44	1.28	1.27	1.30
Cys	0.28	0.26	0.27	0.28	0.24	0.24	0.22	0.25	0.24	0.23	0.21	0.21
Glu	3.23	3.15	3.00	3.17	2.69	2.77	2.49	2.70	2.61	2.38	2.40	2.42

Gly	0.77	0.75	0.71	0.77	0.65	0.66	0.61	0.65	0.66	0.57	0.56	0.57
Pro	1.08	1.06	1.01	1.04	0.93	0.96	0.88	0.94	0.93	0.84	0.88	0.86
Ser	0.77	0.75	0.72	0.74	0.64	0.64	0.62	0.64	0.63	0.57	0.57	0.58
Tyr	0.62	0.60	0.58	0.60	0.51	0.52	0.46	0.52	0.50	0.45	0.44	0.44
Total AA	17.98	17.66	16.67	17.93	14.98	15.31	13.95	15.11	14.56	13.30	13.29	13.33

---

[2] Provided the following quantities of vitamins and micro minerals per kilogram of complete diet: Vitamin A as retinyl acetate, 11,128 IU; vitamin D$_3$ as cholecalciferol, 2,204 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.58 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B$_{12}$, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin as nicotinamide and nicotinic acid, 44 mg; folic acid, 1.58 mg; biotin, 0.44 mg; Cu, 10 mg as copper sulfate; Fe, 125 mg as iron sulfate; I, 1.26 mg as potassium iodate; Mn, 60 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; and Zn, 100 mg as zinc oxide.

Table 8. Concentration of digestible and metabolizable energy, and apparent total tract digestibility (ATTD) of energy in corn that was ground to different particle sizes, as-fed basis, Exp. 1[1]

Item	Corn					*P*-value	
	339 μm	485 μm	677 μm	865 μm	Pooled SEM	Linear	Quadratic
GE intake, kcal	3,500	3,497	3,587	3,425	133.17	0.91	0.85
GE in feces, kcal	325.9	341.8	385.6	386.9	29.62	0.16	0.39
GE in urine, kcal	106.5	100.9	87.6	94.3	10.32	0.12	0.16
ATTD of GE, %	91.6	90.3	89.2	88.7	0.51	< 0.01	< 0.01
DE, kcal/kg	3,547	3,492	3,441	3,402	24.58	0.01	0.01
DE, kcal/kg DM	4,097	4,035	3,978	3,932	28.40	0.02	0.02
ME, kcal/kg	3,432	3,371	3,346	3,311	19.54	< 0.01	< 0.01
ME, kcal/kg DM	3,964	3,895	3,868	3,826	22.58	< 0.01	< 0.01

[1] Data are means of 10 observations per treatment.

Table 9. Effect of particle size on apparent total tract digestibility (ATTD) and standardized total tract digestibility (STTD) of P in corn, Exp. 1[1]

Item	Corn		*P*-value

	339 μm	485 μm	677 μm	865 μm	Pooled SEM	Linear	Quadratic
Feed intake, g DM/d	782.2	778.1	800.8	796.8	33.80	0.58	0.95
P intake, g/d	2.57	2.60	2.67	2.48	0.12	0.63	0.22
P in feces, %	2.65	2.56	2.31	2.15	0.12	< 0.01	0.91
P output, g/d	1.81	1.79	1.84	1.71	0.12	0.49	0.44
Absorbed P, g/d	0.76	0.81	0.83	0.77	0.10	0.92	0.69
ATTD of P, %	29.62	30.99	31.15	31.26	3.32	0.67	0.81
Basal EPL,[2] mg/d	156.44	155.62	160.15	159.35	6.76	0.58	0.95
STTD of P[3], %	37.79	37.12	37.27	37.38	2.99	0.99	0.87

[1] Data are means of 10 observations per treatment.

[2] EPL = basal endogenous P loss. The daily basal EPL was calculated by multiplying daily DMI by 200 mg/kg DMI (Stein, 2011).

[3] Values for STTD were calculated by correcting values for ATTD for basal EPL.

Table 10. Apparent ileal digestibility (AID) of CP and AA (%) in corn that was ground to different particle sizes and fed to growing pigs, Exp. 2[1]

	Corn					*P*-value	
Item	338 μm	485 μm	677 μm	865 μm	Pooled SEM	Linear	Quadratic
CP, %	48.88	51.22	44.18	44.74	5.64	0.11	0.94
Indispensable AA, %							
Arg	71.40	73.09	73.02	70.74	2.87	0.59	0.51
His	72.44	74.80	75.43	73.86	2.73	0.54	0.23
Ile	60.10	63.12	63.46	63.16	4.85	0.66	0.47
Leu	77.84	78.67	79.74	76.56	2.45	0.53	0.16
Lys	54.75	54.93	51.84	55.57	6.59	0.73	0.60
Met	76.46	76.68	76.40	75.29	3.05	0.41	0.93
Phe	71.11	73.25	72.83	71.85	3.33	0.81	0.40
Thr	46.49	49.41	52.31	44.14	7.19	0.70	0.19
Trp	52.48	56.46	61.43	42.61	7.10	0.05	< 0.01
Val	61.09	64.34	66.01	66.19	4.73	0.21	0.43
Mean	64.42	66.48	67.25	64.09	4.06	0.64	0.48
Dispensable AA, %							
Ala	69.08	67.92	67.35	66.04	3.62	0.15	0.95
Asp	61.99	61.74	62.54	62.20	4.67	0.83	0.97
Cys	62.72	63.92	67.25	65.29	3.99	0.18	0.30
Glu	76.82	77.14	77.65	75.01	2.65	0.33	0.38
Gly	42.67	29.70	28.12	21.32	6.35	< 0.01	0.44
Ser	66.91	66.02	69.52	62.50	3.69	0.30	0.18

Tyr	63.54	64.64	63.19	61.96	4.63	0.26	0.70
Mean	63.39	61.58	62.23	59.19	3.87	< 0.01	0.87
All AA	63.99	64.46	65.18	62.02	3.71	0.19	0.70

[a-d]Means within a row lacking a common superscript letter differ ($P < 0.05$).

[1] Data are least squares means of 10 observations.

Table 11. Standardized ileal digestibility (SID) of CP and AA (%) in corn that was ground to different particle sizes and fed to growing pigs, Exp. 2[1]

	Corn					*P*-value	
Item	338 μm	485 μm	677 μm	865 μm	Pooled SEM	Linear	Quadratic
CP, %	75.46	77.21	73.75	72.78	5.63	0.28	0.83
Indispensable AA, %							
Arg	89.22	93.25	94.88	92.04	2.69	0.33	0.07
His	80.85	83.22	84.27	82.29	2.73	0.47	0.17
Ile	73.87	76.32	77.74	76.38	4.85	0.68	0.38
Leu	84.14	85.05	86.34	83.03	2.45	0.63	0.14
Lys	74.78	75.83	73.61	74.32	6.53	0.60	0.98
Met	82.65	82.87	83.05	81.49	3.04	0.47	0.76
Phe	80.58	82.72	82.83	81.61	3.33	0.97	0.34
Thr	66.94	70.71	74.45	66.41	7.19	0.99	0.15
Trp	70.61	78.22	83.19	69.86	7.10	0.86	0.01
Val	74.14	77.39	79.80	78.89	4.73	0.22	0.29
Mean	77.78	80.56	82.02	78.63	4.06	0.79	0.36

Indispensable AA, %							
Ala	82.49	81.61	81.56	80.04	3.62	0.23	0.91
Asp	77.50	77.59	79.02	78.08	4.67	0.95	0.79
Cys	74.02	76.08	79.33	76.61	3.95	0.25	0.25
Glu	84.25	84.76	85.50	82.71	2.65	0.42	0.30
Gly	84.76	95.45	98.14	87.18	9.04	0.75	0.08
Ser	81.70	82.46	85.44	79.60	3.69	0.68	0.15
Tyr	76.55	78.30	78.21	76.36	4.63	0.56	0.44
Mean	80.18	82.32	83.89	80.08	3.87	0.01	0.43
All AA	78.77	81.28	82.79	79.23	3.72	0.33	0.47

[a-d] Means within a row lacking a common superscript letter differ ($P < 0.05$).

[1] Data are least squares means of 10 observations.

[2] Values for SID were calculated by correcting the values for AID for basal ileal endogenous losses. Basal ileal endogenous losses were determined (g/kg of DMI) as CP, 21.50; Arg, 0.84; His, 0.18; Ile, 0.37; Leu, 0.60; Lys, 0.56; Met, 0.09; Phe, 0.37; Thr, 0.59; Trp, 0.13; Val, 0.51; Ala, 0.77; Asp, 0.86; Cys, 0.18; Glu, 1.06; Gly, 2.20; Ser, 0.51; and Tyr, 0.32.

Table 12. Growth performance of pigs fed diets containing corn that was ground to different particle sizes[1]

Item	339 µm	485 µm	677 µm	865 µm	Pooled SEM	*P*-value
BW, kg						
Day 0	32.00	32.19	31.93	31.97	0.44	0.41

Day 30	61.86	62.33	62.07	62.81	1.18	0.77
Day 60	93.72	93.83	94.10	94.72	2.16	0.93
Day 92	129.81	130.25	128.58	129.97	2.90	0.93
ADG, g/d						
Day 30	1.00	1.00	1.00	1.03	0.03	0.73
Day 60	1.06	1.05	1.07	1.06	0.04	0.96
Day 92	1.03	1.04	0.98	1.01	0.17	0.50
Day 0 to 92	1.03	1.03	1.02	1.03	0.03	0.97
ADFI, g/d						
Day 30[2]	2.15	2.13	2.13	2.11	0.07	0.90
Day 60	3.11	3.04	3.02	3.01	0.12	0.70
Day 92	3.47	3.44	3.32	3.34	0.12	0.21
Day 0 to 92	2.94	2.90	2.85	2.81	0.10	0.40
G:F						
Day 30	0.47	0.47	0.47	0.49	0.01	0.11
Day 60[2]	0.34	0.35	0.35	0.35	0.01	0.40
Day 92	0.30	0.30	0.30	0.31	0.01	0.26
Day 0 to 92[2]	0.35	0.36	0.36	0.37	0.01	0.10

---

[1] Data are means of 18 observations per treatment, except for the treatment with corn particle size of 677 μm, which had only 17 observations.

[2] Interactions between particle size and sex were analyzed but were not significant except for ADFI (day 30), G:F (day 60), G:F (day 0 to 92). The ADFI (day 30) was not different ($P > 0.05$) for barrows fed the diets containing corn ground to a different particle sizes. However, gilts fed dietary treatments containing corn ground to a particle size of 865 μm had less ($P < 0.05$) ADFI (day 30) than gilts fed the diet containing corn ground to 339 μm. Likewise, gilts fed the diets containing corn ground to 485, 677, and

865 μm had a greater ($P < 0.01$) G:F (day 60) compared with gilts fed the diet containing corn ground to 339 μm, but G:F (day 60) of barrows was not influenced by particle size.

Table 13. Weights of carcass and body components of finishing pigs fed diets containing corn that was ground to different particle sizes[1]

Item	339 μm	485 μm	677 μm	865 μm	Pooled SEM	*P*-value
Live wt, kg	127.38	127.35	126.96	127.45	2.88	0.99
Dressing[2], %	80.29	79.82	79.78	79.30	0.31	0.06
FFL[3], %	52.74	51.71	53.06	53.29	0.99	0.41
Hot carcass wt, kg	102.31	101.67	101.30	101.10	2.44	0.95
Back fat, cm	2.25	2.48	2.22	2.23	0.19	0.45
Loin eye area, cm	52.92	51.32	53.44	54.52	1.43	0.33
pH at LEA[4]	5.62	5.63	5.57	5.60	0.03	0.34
Liver wt, kg	1.74	1.76	1.78	1.81	0.05	0.65
Heart wt, kg	0.47	0.49	0.51	0.48	0.02	0.27
Kidney wt, kg	0.45	0.47	0.46	0.44	0.01	0.21
Spleen wt, kg	0.18	0.19	0.17	0.18	0.01	0.17
Stomach wt, kg	0.55	0.55	0.56	0.56	0.02	0.83
Empty viscera[5] wt,	2.52^{a}	2.72^{b}	2.65^{b}	3.01^{b}	0.11	< 0.01

[a-b] Means within a row lacking a common superscript letter differ ($P < 0.05$).

[1] Data are means of 18 observations per treatment, except for the treatment with corn particle size of 677 μm, which had only 17 observations.

[2] Dressing, % = HCW / live wt × 100.

[3] FFL, % = carcass fat-free lean as calculated from NPPC (1999): pounds fat free lean = 8.588 – (21.896 × 10th rib fat depth, in.) + (0.465 × HCW, lb.) + (3.005 × 10th rib loin muscle area, sq. in.), (pounds FFL / HCW) × 100 = %FFL.

[4] pH was recorded at the 10th rib.

[5] Empty viscera = weight of the emptied intestinal tract.

Table 14. Measured pH in contents of stomach, ileum, cecum, and rectum and concentration of volatile fatty acids (cecal content) of finishing pigs fed diets containing corn that was ground to different particle sizes[1]

Item	339 μm	485 μm	677 μm	865 μm	Pooled SEM	*P*-value
pH						
Stomach	4.11	4.49	4.99	4.86	0.42	0.33
Ileum	6.82	6.87	6.86	6.74	0.09	0.59
Cecum	6.64^{a}	6.54^{a}	6.20^{b}	6.04^{b}	0.09	< 0.01
Colon	6.23^{a}	6.20^{a}	5.94^{b}	5.85^{b}	0.08	< 0.01
Short-chain Fatty acid, ug/ml						
Acetate	1825.81^{c}	1973.39^{bc}	2285.63^{ab}	2536.64^{a}	135.86	< 0.01
Propionate	617.79^{c}	690.32^{bc}	794.26^{ab}	872.49^{a}	48.29	< 0.01
Butyrate	226.92^{c}	390.74^{b}	611.02^{a}	701.68^{a}	56.84	< 0.01
Branch-chain Fatty acid, ug/ml						
Isobutyrate	76.05^{a}	66.78^{ab}	59.39^{b}	61.66^{b}	5.61	0.05
Isovalerate	114.99	104.61	91.95	93.73	7.93	0.06
Valerate	87.12	91.08	88.54	104.59	8.24	0.26

[a-c] Means within a row lacking a common superscript letter differ ($P < 0.05$).

[1] Data are means of 18 observations per treatment, except for the treatment with corn particle size of 677 µm, which had only 17 observations.

Figures:

Figure 1. Distribution of particle size in corn used in Exp. 1 and 2.