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Effects of reducing the particle size of corn grain on the concentration of digestible and metabolizable energy and on the digestibility of energy and nutrients in corn grain fed to growing pigs

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ABSTRACT

Two experiments were conducted to determine the apparent ileal digestibility (AID) of starch and gross energy (GE), the standardized ileal digestibility (SID) of crude protein (CP) and amino acids (AA), the concentration of digestible energy (DE) and metabolizable energy (ME), and the standardized total tract digestibility (STTD) of P in corn ground to 4 different particle sizes (i.e., 865, 677, 485, and 339 μm). In Experiment 1, 10 growing barrows (initial body weight: 29.2 ± 1.4 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. 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 965.5 g/kg corn (as-fed basis) as the only source of starch, GE, and AA. Results indicated that the AID of starch and GE was increased (linear, $P < 0.05$) as the particle size decreased from 865 to 339 μm. With the exception of Trp, there was no impact of corn particle size on the SID of CP or any indispensable AA. In Experiment 2, 40 growing barrows (initial body weight: 22.8 ± 2.1 kg) were placed in metabolism crates and allotted to a randomized complete block design with 4 diets and 10 replicate pigs per diet. Each diet contained one of the 4 batches of corn used in Experiment 1 (977.0 g/kg, as-fed basis) as the only source of GE and P. Results indicated that the concentration of ME was 16.02, 16.19, 16.31, and 16.60 MJ/kg dry matter for corn ground to a mean particle size of 865, 677, 485, and 339 μm, respectively. The ME concentration increased (linear and quadratic, $P < 0.01$) as the particle size decreased. The average STTD of P in the 4 batches of corn was 37.4% and no differences among treatments were observed. In conclusion, decreasing the particle size of corn from 865 to 339 μm linearly increased the concentration of DE and ME and the AID of starch and GE in corn, but the particle size of corn did not affect the STTD of P or the SID of indispensable AA and CP.

1. Introduction

Grinding of feed ingredients is used to reduce the particle size and increase energy and nutrient digestibility (Kim et al., 2002; Laurinen et al., 2000; Mavromichalis et al., 2000; Wondra et al., 1995d) and it is usually 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 is milled to an average particle size of 640–650 μm (Kim et al., 2002; Wondra et al., 1995b), but the apparent total tract digestibility (ATTD) of energy, dry matter (DM), and N in corn fed to finishing pigs or sows increased as the particle size of the grain was reduced (Healy et al., 1994; Wondra et al., 1995a,b,c,d). There was also a tendency for an increase in the standardized ileal digestibility (SID) of amino acids (AA) in soybean meal as particle size was reduced (Fastinger and Mahan, 2003), but there was no effect of particle size on the ATTD of P in distillers dried grains with solubles (DDGS; Liu et al., 2012). However, there are no data that demonstrate the effects of particle size on the SID of AA, the apparent ileal digestibility (AID) of starch and gross energy (GE) or the standardized total tract digestibility (STTD) of P in corn grain.

Therefore, the objectives of the present experiments were to determine the concentration of digestible energy (DE) and metabolizable energy (ME), the STTD of P, the AID of starch and GE, and the SID of AA and crude protein (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 in the digestibility of AA, starch, GE, and P in corn, as particle size is reduced was tested.

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2. 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 experiments were the offspring of G-performer boars mated to F-25 gilts (Genetiporc, Alexandria, MN, U.S.). The same batch of corn (Pioneer P0528) was used in all diets in both experiments and the corn was grown in the state of Iowa in 2011. The corn grain was first rolled using an automatic roller mill (Model CSU 500, 2 stage; Automatic Equipment Mfg. Co., Pender, NE, U.S.) to obtain a mean particle size of 2000 μm. The rolled grain was then divided into 4 batches that were ground using a hammer mill (Model #EL-9506-TF; Bliss Industries, Ponca City, OK, U.S.) with 15.88, 9.53, 3.97, or 1.19 mm screens to obtain average final particle sizes of 865, 677, 485, and 339 μm, respectively (Pioneer Hi-Bred Feed Mill, Johnston, IA, U.S.). The grain was stored at 15 °C until used (Table 1).

2.1. Diets, animals, and experimental design

Experiment 1 was designed to determine the SID of CP and AA and the AID of starch and GE in the 4 batches of corn ground to different particle sizes. Ten growing barrows (initial BW: 29.2 ± 1.4 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^2) in an environmentally controlled room. A feeder and a nipple drinker were installed in each pen.

Five diets were formulated (Tables 2 and 3). Four of the diets each contained one of the 4 batches of corn (965.5 g/kg, as-fed basis) and corn was the only ingredient contributing AA, CP, starch, and GE to the diet. These diets were formulated to contain approximately 16.5 MJ ME/kg and 70 g CP/kg. The last diet was a N-free diet that was used to measure basal endogenous losses of AA and CP. Chromic oxide (4.0 g/kg) was included in all diets as an indigestible marker and vitamins and minerals were included in

Table 1
Chemical and physical composition of the corn grain used in both experiments (as-fed basis).

Item	Corn particle size (μm)			
	865	677	485	339
Gross energy (MJ/kg)	16.41	16.33	16.39	16.20
Dry matter (g/kg)	865.4	864.0	867.1	863.0
Crude protein (g/kg)	70.8	72.3	72.5	70.0
Ash (g/kg)	11.5	13.9	12.3	11.0
Acid hydrolyzed ether extract (g/kg)	34.5	35.1	35.3	35.7
Neutral detergent fiber (g/kg)	110.6	100.1	92.9	92.5
Acid detergent fiber (g/kg)	24.1	22.7	22.4	19.1
Starch (g/kg)	629.0	611.9	627.3	644.2
P (g/kg)	3.1	3.4	3.0	2.9
Ca (g/kg)	0.3	0.3	0.3	0.3
Indispensable amino acids (g/kg)				
Arg	3.5	3.7	3.5	3.5
His	2.0	2.1	2.0	2.0
Ile	2.4	2.6	2.5	2.4
Leu	8.5	8.4	8.3	8.3
Lys	2.5	2.6	2.5	2.5
Met	1.4	1.4	1.3	1.4
Phe	3.5	3.5	3.5	3.5
Thr	2.5	2.4	2.5	2.5
Trp	0.6	0.5	0.5	0.5
Val	3.5	3.8	3.6	3.5
Dispensable amino acids (g/kg)				
Ala	5.1	5.2	5.1	5.1
Asp	4.9	5.0	4.9	4.9
Cys	1.5	1.5	1.4	1.5
Glu	12.8	12.5	12.6	12.6
Gly	3.0	3.0	3.0	3.0
Pro	6.4	6.2	6.4	6.3
Ser	3.2	3.0	3.0	3.1
Tyr	2.0	2.2	2.0	2.1
Total amino acids	69.3	69.6	68.6	68.7

Table 2
Composition of experimental diets containing corn that was ground to different particle sizes and in the N-free diet used in Experiment 1 and 2 (as-fed basis)[a].

Item (g/kg)	Experiment 1 Corn	N-free	Experiment 2 Corn
Ground corn	965.5	–	977.0
Sucrose	–	200.0	–
Cornstarch	–	676.0	–
Solka floc	–	40.0	–
Soybean oil	–	40.0	–
Ground limestone	8.5	2.0	16.0
Magnesium oxide	–	1.0	–
Potassium carbonate	–	4.0	–
Dicalcium phosphate	15.0	26.0	–
Sodium chloride	4.0	4.0	4.0
Chromic oxide	4.0	4.0	–
Vitamin mineral premix[b]	3.0	3.0	3.0
Total	1000	1000	1000

[a] Four diets that contained corn ground to a mean particle size of 865, 677, 485, or 339 μm were formulated within each experiment.
[b] 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 nutrient composition of experimental diets, Experiment 1 (as-fed basis).

Item	Corn particle size (μm)				N-free[a]
	865	677	485	339	
Gross energy (MJ/kg)	15.40	15.49	15.60	15.60	15.71
Dry matter (g/kg)	867.2	865.9	865.8	865.9	908.7
Crude protein (g/kg)	66.5	62.1	71.6	70.0	3.0
Ash (g/kg)	45.5	39.3	39.3	40.4	39.1
Neutral detergent fiber (g/kg)	88.3	83.4	81.3	87.5	46.2
Acid detergent fiber (g/kg)	19.7	21.8	21.6	20.1	31.9
Starch (g/kg)	662.2	617.9	597.1	631.3	–
Indispensable amino acids (g/kg)					
Arg	3.3	3.0	3.3	3.4	0.1
His	1.9	1.8	1.9	1.9	0.0
Ile	2.4	2.2	2.4	2.3	0.1
Leu	8.0	7.8	8.1	8.2	0.3
Lys	2.3	2.2	2.3	2.4	0.1
Met	1.3	1.2	1.3	1.3	0.0
Phe	3.3	3.2	3.4	3.4	0.2
Thr	2.3	2.3	2.4	2.5	0.1
Trp	0.4	0.5	0.5	0.6	0.3
Val	3.5	3.2	3.4	3.4	0.0
Dispensable amino acids (g/kg)					
Ala	4.8	4.7	4.9	5.0	0.3
Asp	4.7	4.5	4.7	4.8	0.2
Cys	1.4	1.3	1.3	1.4	0.0
Glu	12.0	11.7	12.1	12.4	0.4
Gly	2.9	2.7	2.9	3.0	0.2
Pro	6.1	5.9	6.2	6.3	0.6
Ser	2.6	2.8	2.7	3.0	0.1
Tyr	1.9	1.8	2.0	2.1	0.1
Total amino acids	65.1	62.8	65.8	67.4	3.1

[a] N-free = nitrogen free diet.

Table 4
Analyzed composition of experimental diets containing corn that was ground to different particle sizes, Experiment 2 (as-fed basis).

Item	Corn particle size (μm)			
	865	677	485	339
Gross energy (MJ/kg)	15.91	15.64	15.81	15.84
Dry matter (g/kg)	865.4	865.0	865.4	865.7
Crude protein **(g/kg)**	68.5	68.5	69.7	67.7
Ash (g/kg)	25.4	28.6	26.0	29.0
P (g/kg)	3.1	2.8	2.6	2.8
Ca (g/kg)	5.1	7.5	6.6	6.1
Neutral detergent fiber (g/kg)	97.8	97.2	80.3	82.6
Acid detergent fiber (g/kg)	18.9	18.5	18.0	15.5

all diets to meet or exceed requirement estimates (National Research Council, 1998).

Experiment 2 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 that were used in Experiment 1. Forty barrows (initial BW 22.8 ± 2.1 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, which allowed for the total, but separate, collection of urine and fecal materials from each pig.

Four corn-based diets that contained 977.0 g/kg corn were formulated (Tables 2 and 4) to contain approximately 16.5 MJ ME/kg and 70 g/kg of CP. Vitamins and minerals were included in the diets to meet the requirement for growing pigs (National Research Council, 1998) with the exception that no inorganic P was used, and all 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., 865, 677, 485, and 339 μm) as explained for Experiment 1.

2.2. Feeding and sample collection

In Experiment 1, all pigs were fed at a level of 3 times the maintenance energy requirement (i.e., 0.444 MJ ME per $kg^{0.75}$; National Research Council, 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 was provided at each meal in addition to the allotted quantity of the experimental diet to reduce the effects of feeding diets that did not meet the pig's requirement for all AA as has been previously suggested (Pedersen et al., 2007). The AA mixture contained the following ingredients (g/kg, as-fed basis): 412 g L-Gly; 205 g L-Lys · HCl, 33 g DL-Met; 84 g L-Thr; 27 g L-Trp; 63 g L-Ile; 74 g L-Val; 37 g L-His; and 65 g L-Phe.

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 −20 °C to prevent bacterial degradation of AA in the digesta.

In Experiment 2, pigs were provided feed and water and individual pig weights were recorded as explained for Experiment 1. The experimental diets were fed to pigs for 12 d. The initial 5 d were considered an adaptation period to the diet, and urine and fecal samples were collected for 5 d according to standard procedures using the marker to marker approach (Adeola, 2001). Each crate contained a screen and a funnel placed below the slatted floor of the crates allowed for the total, but separate, collection of feces and urine from each pig. Feces were collected twice daily and stored at −20 °C immediately after collection. Urine buckets were placed under the metabolism cages to permit total collection. They 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 −20 °C.

2.3. Sample analysis

At the conclusion of Experiment 1, ileal samples were thawed, mixed within animal and diet, and a subsample was collected for chemical analysis. Ileal digesta samples were lyophilized (General Purpose Freeze Drier; Virtis SP Scientific; New York, U.S.) and ground through a 1 mm screen (Wiley Mill Model 4; Thomas Scientific; Swedesboro, NJ, U.S.). All samples of digesta, diets, and each batch of corn were analyzed for GE using bomb calorimetry (Model 6300, Parr Instruments, Moline, IL, U.S), dry matter (Method 930.15; AOAC Int., 2007), CP by combustion (Method 999.03; AOAC Int., 2007) using a Rapid N cube apparatus (Elementar Americas Inc, Mt. Laurel, NJ, U.S.), starch (Method 76-13; AACC Int., 2000) using a modified starch assay kit (product code STA-20, Sigma, St. Louis, MO, U.S.), and AA [Method 982.30 E (a, b, c); AOAC Int., 2007]. Chromium concentrations of diets and ileal digesta were also determined (Method 990.08; AOAC Int. 2007). All diet and samples of corn were also analyzed for ash (Method 942.05; AOAC Int., 2007), acid detergent fiber (ADF; Method 973.18; AOAC Int., 2007), and neutral detergent fiber (NDF; Holst, 1973). Corn samples were analyzed for acid hydrolyzed ether extract, 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, U.S.) 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). Bulk density, filling angle of repose, and water binding capacity in the corn grain were determined as described by Cromwell et al. (2000), Appel (1994), and Robertson et al. (2000), respectively. Analyses for AA, detergent fiber, and minerals were conducted at the University of Missouri (Colombia, MO, USA), and all other analyses were completed at the University of Illinois (Urbana, IL, U.S).

At the conclusion of Experiment 2, urine samples were thawed and mixed, and a subsample was collected. Fecal samples were dried at 65 °C in a forced-air oven and ground through a 1-mm screen in a Wiley mill (Model 4; Thomas Scientific, Swedesboro, NJ, U.S.) before analyses. Urine samples were prepared and lyophilized before energy analysis as previously described (B.G. Kim et al., 2009). Diets were analyzed for CP, ash, NDF, ADF, and Ca as described for Experiment 1, and diets, feces, and urine samples were analyzed for GE as described for Experiment 1. Diets and fecal samples were also analyzed for DM and P as described for Experiment 1.

Particle size distribution and mean particle size of the corn samples were determined using 100 g of grain that was placed on 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 greater to the smallest aperture size. The test sieves were then located in a vibratory sieve shaker for 10 min and no flow agents were added to the test sieves. The feedstuff material in each of the test sieves was recorded and weighed for calculations of particle size distribution and mean particle size. After determination of the mean particle size as described by ASAE (2008), the surface area was calculated using mean particle size of the grain as a reference (ASAE, 2008).

Table 5
Physical composition of corn grains used in both experiments (as fed basis)[a].

Item	Corn particle size, μm				SEM	*P*-value	
	865	677	485	339		Linear	Quadratic
SD[b] of particle size	3.15	3.20	2.92	1.89	0.02	< 0.01	< 0.01
Surface area (cm^2/g)	101.4	132.1	166.6	164.5	1.97	< 0.01	< 0.01
Filling angle of repose (deg)	46.8	50.7	54.9	57.4	0.13	< 0.01	0.07
Bulk density (g/L)	650.6	631.5	601.4	564.5	1.91	< 0.01	< 0.01
Water binding capacity (g/g)	2.2	2.2	2.3	2.3	0.03	0.19	0.71

[a] Data are least square means of 2 observations per treatment.
[b] SD = Standard deviation.

2.4. Calculations and statistical analysis

In Experiment 1, values for AID, basal endogenous losses, and SID of CP and AA in the diets were calculated (Stein et al., 2007) and the AID of starch and GE was calculated using the same equation as for AID of CP and AA. Data were analyzed by ANOVA using the MIXED procedure (SAS Inst. Inc., Cary, NC, U.S.). Least Squares Means were used to calculate mean values for each independent variable. Homogeneity of variances among treatments was confirmed using the HOVTEST of SAS. Outliers were determined using the UNIVARIATE procedure of SAS as values that deviated from the treatment mean by more than 1.5 times the interquantile range (Devore and Peck, 1993). Two outliers were detected and removed from the data set (the outliers were from pigs fed the diets containing corn ground to a mean particle size of 865 and 677 μm respectively). Orthogonal polynomial contrasts were used to analyze effects of decreasing corn particle size. The particle size of each batch of corn was used in the calculations to determine the appropriate coefficients for unequally spaced particle sizes of corn using the interactive matrix language procedure in SAS. The pig was the experimental unit, and an α-value of 0.05 was used to assess significance among means and tendencies were considered if $P > 0.05$ and $P \leq 0.10$.

In Experiment 2, the quantities of energy lost in the feces and in the urine, respectively, were calculated, and the DE and ME in each of the 4 diets were calculated (Widmer et al., 2007). By dividing the DE and ME in the diets by the inclusion rate of corn in the diets (0.977), the DE and ME in each batch of corn was calculated (Adeola, 2001). The amount of P in the feces was subtracted from the P in the diet and the ATTD of P was calculated (Almeida and Stein, 2010) and values for STTD of P were calculated by correcting the ATTD of P for the basal endogenous loss of P (200 mg/kg dry matter intake; Stein, 2011).

Data were analyzed by ANOVA using the Proc Mixed Procedure of SAS as described for Experiment 1. Least Squares Means, homogeneity of variances, and identification of outliers were determined as described for experiment 1, but no outliers were observed. The effect of decreasing the particle size of corn was analyzed by orthogonal polynomial contrasts as described for Experiment 1.

3. Results

Grinding did not change the gross composition of the corn grain and in general, the nutrient composition was in agreement with values for yellow dent corn (NRC, 2012). The standard deviation (SD) of the particle size and bulk density decreased (linear and quadratic, $P < 0.01$) as the particle size decreased from 865 to 339 μm (Table 5). In contrast to the SD, surface area of particle sizes increased (linear and quadratic, $P < 0.01$) as the particle size was reduced. Filling angle of repose also increased (linear $P < 0.01$) as corn particle size was reduced. There were no differences among treatments in water biding capacity.

Table 6
Apparent ileal digestibility (AID) of gross energy, starch, crude protein, and amino acids (%) in corn that was ground to different particle sizes and fed to growing pigs, Experiment 1[a].

Item	Corn particle size (μm)				Pooled SEM	*P*-value	
	865	677	485	339		Linear	Quadratic
GE (%)	66.1	69.2	71.6	74.3	4.77	0.03	0.96
Starch (%)	89.0	92.6	93.9	96.6	1.32	< 0.01	0.82

[a] Data are least squares means of 10 observations, except for the treatments with corn ground to 865 and 677 μm, which had only 9 observations.

Pigs remained healthy during both experiments and easily consumed their diets. In Experiment 1, the AID of starch and GE increased (linear, $P < 0.05$) as the particle size decreased from 865 to 339 μm (Table 6), but only minor differences in the AID of AA were observed (data not shown). The SID of CP and all indispensable and dispensable AA was not affected by the particle size of corn (Table 7), except for the SID of Trp, which had the greatest value at the intermediate particle sizes (quadratic, $P < 0.05$). The average SID of indispensable and dispensable AA was also not different among diets.

In Experiment 2, there were no differences in GE intake or in fecal or urine excretion of GE among pigs fed diets containing corn ground to different particle sizes (Table 8). However, the ATTD of GE was increased (linear and quadratic, $P < 0.01$) as the particle size decreased from 865 to 339 μm. The concentration of DE (as-fed and dry matter basis) increased (linear and quadratic, $P < 0.05$) as the particle decreased from 865 to 339 μm. Likewise, the ME concentration, calculated on an as-fed or on a dry matter basis, increased from 13.86 to 14.37 MJ/kg and from 16.02 to 16.60 MJ/kg, respectively, when corn particle size decreased from 865 to 339 μm.

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

4. Discussion

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

Table 7
Standardized ileal digestibility (SID) of crude protein and amino acids (%) in corn that was ground to different particle sizes and fed to growing pigs, Experiment 1[a,b].

Item	Corn particle size (μm)				Pooled SEM	*P*-value	
	865	677	485	339		Linear	Quadratic
Crude protein (%)	71.7	72.2	77.2	75.5	4.97	0.28	0.83
Indispensable amino acids (%)							
Arg	93.1	92.4	94.8	92.8	3.03	0.85	0.84
His	83.0	83.9	83.2	80.8	2.30	0.33	0.26
Ile	75.3	76.8	76.3	73.9	4.23	0.68	0.38
Leu	83.5	86.0	85.0	84.1	2.06	0.84	0.19
Lys	72.3	72.5	74.9	74.7	5.84	0.59	0.99
Met	82.3	82.4	82.9	82.6	2.47	0.80	0.95
Phe	80.8	82.1	82.7	80.6	2.91	0.96	0.34
Thr	68.9	73.6	70.7	66.9	5.86	0.63	0.23
Trp	70.3	78.6	78.2	70.6	6.34	0.87	0.02
Val	77.8	79.0	77.4	74.1	4.13	0.22	0.29
Mean	80.8	81.8	81.3	80.0	3.34	0.77	0.54
Dispensable amino acids (%)							
Ala	79.3	80.8	81.6	82.5	3.17	0.23	0.91
Asp	77.1	78.2	77.6	77.5	4.08	0.95	0.79
Cys	77.8	78.9	76.1	74.0	3.23	0.13	0.36
Glu	83.5	85.1	84.7	84.2	2.15	0.74	0.44
Gly	82.3	88.2	95.0	84.8	8.11	0.57	0.26
Pro	80.7	85.3	82.5	81.7	3.10	0.96	0.21
Ser	75.2	77.0	78.3	76.5	4.04	0.56	0.45
Tyr	89.6	90.9	93.7	92.7	4.15	0.40	0.80
All amino acids	84.7	84.2	87.5	86.4	3.46	0.39	0.98

[a] Data are least squares means of 10 observations, except for the treatments with corn ground to 865 and 677 μm, which had only 9 observations.
[b] Values for SID were calculated by correcting the values for apparent ileal digestiblity for basal ileal endogenous losses. Basal ileal endogenous losses were determined (g/kg dry matter intake) as crude protein, 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 8
Concentration of digestible energy (DE) and metabolizable energy (ME), and apparent total tract digestibility (ATTD) of gross energy (GE) in corn that was ground to different particle sizes, Experiment 2 (as-fed basis)[a].

Item	Corn particle size (μm)				Pooled SEM	*P*-value	
	865	677	485	339		Linear	Quadratic
GE intake (MJ/d)	14.34	15.02	14.64	14.65	0.56	0.91	0.85
GE in feces (MJ/d) MJ/d	1.62	1.61	1.43	1.36	0.12	0.16	0.39
GE in urine (MJ/d) MJ/d	0.39	0.37	0.42	0.45	0.04	0.12	0.16
ATTD of GE (%)	88.7	89.2	90.3	91.6	0.51	< 0.01	< 0.01
DE (MJ/kg)	14.24	14.41	14.62	14.85	0.10	0.01	0.01
DE (MJ/kg dry matter)	16.46	16.66	16.89	17.15	0.12	0.02	0.02
ME (MJ/kg)	13.86	14.01	14.11	14.37	0.08	< 0.01	< 0.01
ME (MJ/kg dry matter)	16.02	16.19	16.31	16.60	0.09	< 0.01	< 0.01

[a] 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, Experiment 2[a].

Item	Corn particle size (μm)				Pooled SEM	*P*-value	
	865	677	485	339		Linear	Quadratic
Feed intake (g dry matter/d)	796.8	800.8	778.1	782.2	33.80	0.58	0.95
P intake (g/d)	2.5	2.7	2.6	2.6	0.12	0.63	0.22
P in feces (%)	2.2	2.3	2.6	2.7	0.12	< 0.01	0.91
P output (g/d)	1.7	1.8	1.8	1.8	0.12	0.49	0.44
Absorbed P (g/d)	0.8	0.8	0.8	0.8	0.10	0.92	0.69
ATTD of P (%)	31.3	31.1	31.0	29.6	3.32	0.67	0.81
STTD of P[b](%)	37.4	37.3	37.1	37.8	2.99	0.99	0.87

[a] Data are means of 10 observations per treatment.
[b] Values for STTD were calculated by correcting values for ATTD for basal endogenous phosphorus losses (200 mg/kg dry matter intake; Stein, 2011).

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 300 μm or less. In some 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., 1995c,d). By using such an approach, it is not possible to distinguish between effects of mill type and effects of changing particle size. In the present experiments, grains were first rolled and then processed in a hammer mill. By using this approach, we attempted to eliminate the effect of mill type on digestibility values. This type of grinding is also used in many newer feed mills in which a 2-stage or a multistage grinding system is used to minimize variation in particle size and maximize grinding efficiency.

The concentration of GE, CP, dry matter, P, Ca, acid hydrolyzed ether extract, and AA in the corn used in this experiment is in agreement with recently reported values (NRC, 2012; Pedersen et al., 2007; Soares et al., 2011). The decrease in SD and the increase in surface area that was observed as particle size decreased are in agreement with values reported by Wondra et al. (1995d). This is likely a result of the larger screens used to grind to a large particle size, which allows both small and large particles to pass whereas the smaller screens used to grind to the smaller particle size only will allow small particles to pass, thus resulting in reduced SD. The increased filling angle of repose as the mean corn particle size decreased indicates that as particle size is reduced, flowability of the feed may also be reduced. This observation concurs with data demonstrating that diets containing finely ground DDGS or soybean meal have a poor flowability compared with diets containing coarser ground DDGS and soybean meal (Lawrence et al., 2003; Liu et al., 2012). The reduction of bulk density observed as corn particle size decreased may exacerbate the poor flowability of finely ground corn compared with coarsely ground corn because bulk density may be an indicator of efficient handling capacity in bins and feeders (Rosentrater, 2012).

Water binding capacity reflects the amount of water that may be retained after the fiber is stressed (Cho et al., 1997). The lack of differences in water binding capacity among corn ground to different particle sizes indicates that absorption of water is not influenced by the particle size of corn.

Pigs fed ingredients with a reduced particle size may develop gastric ulcers (Mahan et al., 1966; Maxwell et al., 1970; Wondra et al., 1995a) and development of ulcers is considered one of the major reasons for economical losses in the U.S. swine industry (Friendship, 2003). However, because of the short time diets were fed in the present experiments, it was not possible to investigate effects of diets on development of ulcers.

The SID of AA in corn obtained in Experiment 1 is within the range of values reported in previous experiments (Bohlke et al., 2005; NRC, 2012). The fact that particle size of corn did not influence the SID of most AA is in contrast with observations by Fastinger and Mahan (2003) who reported that a reduction in particle size of soybean meal from 949 to 185 μm tended to increase the SID of some indispensable AA. Likewise, the SID of AA in lupins increased as particle size decreased (J.C. Kim et al., 2009). We do not have an explanation for the significant quadratic effect of particle size on the SID of tryptophan and this effect has not been reported in previous experiments.

Values for the AID of starch that were observed in this experiment for corn ground to 485 or 677 μm concur with values reported by Everts et al. (1996) and Cervantes-Pahm et al. (2014). Starch is the main form of energy storage in grains (Liu, 2012) and it is mainly digested in the small intestine. However, there is a portion of the starch that is not well digested, and this starch will be fermented in the large intestine (Champ, 2004). The concentration of starch in corn used in this experiment concurs with values reported by Li et al. (2006). The increase in the AID of GE and starch in corn that was observed as particle size decreased is likely a result of increased access to the starch granules for α-amylase, which increases starch digestibility (Fastinger and Mahan, 2003; Kim et al., 2002; Reece et al., 1985). The reduced surface area of grain ground to the greater particle size may have contributed to the reduced access for enzymes (Al-Rabadi et al., 2009).

It is likely that the starch that was not digested in the small intestine was fermented in the large intestine (Bach Knudsen, 2011; NRC, 2012). Therefore, synthesis and absorption of short-chain fatty acids is likely greater in corn ground to a mean particle size of 865 μm than in corn ground to 339 μm and digestibility of starch is increased in grain with large surface area due to a small particle size (Al-Rabadi et al., 2009). Our results support the hypothesis that reduction of cereal grain particle size may increase the effectiveness of starch degrading enzymes. However, the fact that AID and SID of CP and AA were not influenced by particle size indicates that protein-digesting enzymes were not hindered by the reduced surface area and greater particle size in the corn ground to 865 μm. Thus, it appears that finer grinding and greater surface area is more important for starch digesting enzymes to gain access to the starch granules than it is for proteases to gain access to dietary proteins, possibly because starch can be more encased in the fiber than proteins. However, differences among feed ingredients may exist and results from this experiment with corn should, therefore, not be extrapolated to other ingredients.

The concentrations of GE, DE, and ME in corn observed in Experiment 2 concur with reported values (NRC, 2012; Rojas et al., 2013; Widmer et al., 2007) and the ATTD of GE was also in agreement with reported values (Baker and Stein, 2009; Pedersen et al., 2007). The DE:ME ratio obtained for all particle sizes is within the range of reported values (NRC, 2012; Widmer et al., 2007). 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. (1995c), when grain with different particle sizes were fed to sows, but in agreement with data 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 ATTD of GE in DDGS and the concentration of DE and ME also increased when pigs were fed 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 was decreased from 1304 to 567 μm, the ATTD of energy was not affected (J.C. Kim et al., 2009). It is not clear why there is this difference among feed ingredients. The observation that there is no difference in GE excreted in the urine among treatments indicates that the entire improvement in ME of corn that was observed as particle size was reduced is due to the increased energy digestibility.

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 also concurs with observations by Liu et al. (2012), who reported that reduction of particle size in DDGS did not influence the ATTD of P. Thus, it appears that reduction in particle size or increases in surface area of ground corn grain are not effective in improving P digestibility in pigs. The reason may be that to increase P digestibility in corn, the enzyme phytase is needed and pigs do not secrete phytase in the small intestine.

5. Conclusions

Reducing the particle size of corn from 865 to 339 μm linearly increased the AID of starch and 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, except for tryptophan.

Conflict of interest statement

There are no conflicts of interest.

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