Enhancing digestibility of corn fed to pigs at two stages of growth through management of particle size using a hammermill or a roller mill

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ABSTRACT: The experimental objective was to determine the role of mean particle size (PS), grinding method, and body weight (BW) category on nutrient, fiber, and energy digestibility of corn. A total of 48 barrows were housed in individual pens and randomly assigned to one of six dietary treatments for 11 d at two BW categories (55 kg and 110 kg). The six treatments consisted of corn ground at three different targeted mean PSs (300, 500, and 700 µm) using either a roller mill or a hammermill. Fecal samples were collected for the last 3 d of each feeding period. Titanium dioxide was used as an indigestible marker. Digestibility data were analyzed as a linear mixed model using the MIXED procedure of SAS. Finishing pigs had greater apparent total tract digestibility (ATTD) of dry matter (DM), gross energy (GE), and N than growing pigs ($P = 0.02$, $P = 0.01$, and $P < 0.01$, respectively). The ATTD of DM, GE, and N was similar in pigs fed hammermilled corn across all PS treatments. However, in roller-milled corn, they increased as PS was reduced ($P < 0.05$). The ATTD of acid-hydrolyzed ether extract (AEE) in growing pigs was similar between corn ground at 700 and 500 µm, but it was increased by further reducing PS to 300 µm ($P < 0.05$). In finishing pigs, the ATTD of AEE increased as mean PS decreased from 700 to 300 µm ($P < 0.05$). The ATTD of AEE was similar in hammermilled corn at all three PS treatments. On the other hand, the ATTD of AEE was similar in corn ground in a roller mill to 700 and 500 µm, but it increased when PS was reduced to 300 µm ($P < 0.05$). In conclusion, reducing PS of corn with a roller mill increased digestibility of energy and nutrients, but there was less effect using a hammermill. It is possible that differences in SD, distribution, chemical composition, and the shape of the particles resulting from the two grinding processes help to explain the different response.

Key words: body weight, grinding, hammermill, roller mill, swine

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INTRODUCTION

Digestion and absorption are essential processes because they determine the uptake of nutrients and energy from the diet. Various approaches have been adopted to optimize the process of digestion, the most frequent being grinding to reduce particle size (PS) of feed ingredients.

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By reducing PS, surface area increases and nutrients become more accessible to enzymes, which in turn improves digestibility (Wondra et al., 1995). However, more definitive data are needed on the impact of PS reduction, and mean PS, within the range of current industry practice (300 to 700 µm). In addition, research is needed to clarify if the digestibility response to PS is also affected by the grinding methods (GMs) used, and the growth stage of the pig.

There are at least two common GMs that are used to economically process feed ingredients: the roller mill and the hammermill. Each delivers different particle shapes due to differences in grinding action, which may imply different impacts on digestion (Wondra et al., 1995). However, a more detailed comprehension of these two GMs is needed to better understand how they affect digestibility outcomes.

Furthermore, digestibility is believed to improve as animals grow. This is attributed to a more developed gastrointestinal tract and the associated increase in digestive capacity, especially as it relates to the fiber fraction of the diet (Noblet and Henry, 1993; Noblet and van Milgen, 2004). It is possible that age-dependent intestinal development may affect the pig's response to a reduction in PS and the GM used to achieve it.

Finally, there are few data on the chemical composition of different sized particles within ground feed. This may be an important piece of information to better understand the digestive response to PS and the impact on the gastrointestinal tract.

Therefore, the overall objective of this study was to determine the role of mean PS, GM, and pig body weight (BW) on nutrient and energy digestibility of corn in the pig. We hypothesized that reducing mean PS would increase digestibility equally using either a hammermill or a roller mill. In addition, we hypothesized that digestibility would increase in finishing pigs compared to growing pigs, independent of the mean PS and the GM used.

MATERIALS AND METHODS

All experimental procedures adhered to guidelines for the ethical and humane use of animals for research according to the Guide for the Care and Use of Agricultural Animals in Research and Teaching (FASS, 2010) and were approved by the Institutional Animal Care and Use Committee at Iowa State University (2-14-7731-S).

Animals Housing, Dietary Treatments, and Experimental Design

A total of 48 barrows, the progeny of C22 or C29 sows × 337 terminal sires (PIC Inc., Hendersonville, TN), were randomly assigned to a 3 × 2 × 2 factorial experimental design: three target mean PSs of corn (300, 500, and 700 µm), two GMs (roller mill and hammermill), and two BW categories (growing pigs with an average initial BW of 54.9 ± 0.6 kg and finishing pigs with an average BW of 110.7 ± 1.4 kg). There were eight observations per treatment.

Pigs were housed in a controlled environment facility in individual pens (Swine Nutrition Farm, Iowa State University, Ames, IA). Each pen included a partially slatted concrete floor, an automatic self-feeder, and a cup drinker. During each test period (growing and finishing), the six experimental diets were delivered two times per day (0800 h and 1600 h) in equal sized meals for 11 d. The two lightest pigs on each treatment received a quantity of feed equivalent to 2.5 and the remaining six pigs 2.7 times the daily estimated requirement for maintenance energy based on the average initial BW of each period (i.e., 197 kcal ME/kg$^{0.60}$; NRC, 2012). All diets were provided in mash form. Pigs had ad libitum access to water.

The same animals remained on test over the two BW categories but they were re-randomized to treatment following the growing period. Pigs were not permitted to receive the same experimental treatment in the growing and in the finishing periods. For the 45 d between the two BW periods, pigs were fed a common nutrient-adequate commercial growing pig diet. The daily feed allowance and method of presentation were calculated in the same manner as used during the growing period.

Before mixing the experimental diets, corn was ground to one of three mean PSs (300, 500, and 700 µm), using either a hammermill (model 22115; Bliss Industries, Ponca City, OK) or a roller mill (model 924; RMS Roller Grinder, Harrisburg, SD) at the O.H. Kruse Feed Technology Innovation Center (Kansas State University, Manhattan, KS). The experimental diets were manufactured by mixing each ground corn treatment with the remaining ingredients, according to the formulations presented in Table 1. All diets contained titanium dioxide (TiO_2; as an indigestible marker) and were further supplemented to ensure the pigs' requirements for vitamins and minerals were met. However, there was no inclusion of other plant- or animal-based proteins, fats, or synthetic sources of amino acids. This approach ensured that corn was

Table 1. Ingredient composition of the experimental diets[1]

Ingredient	Amount, %
Corn	96.43
Monocalcium phosphate	1.08
Calcium carbonate	1.19
Salt	0.50
Vitamin premix[2]	0.20
Mineral premix[3]	0.20
Titanium dioxide	0.40

[1]There were six experimental diets in total: three PSs (300, 500, and 700 µm) at each of two GMs: hammermill or roller mill.

[2]Vitamin premix provided the following (per kilogram diet): 6,125 IU of vitamin A, 700 IU of vitamin D3, 50 IU of vitamin E, 3 mg of menadione (to provide vitamin K), 11 mg of riboflavin, 27 mg of D-pantothenic acid, 0.05 mg of vitamin B12, and 56 mg of niacin.

[3]Mineral premix provided the following (per kg diet): 220 mg of Fe (ferrous sulfate), 220 mg of Zn (zinc sulfate), 52 mg of Mn (manganese sulfate), 22 mg of Cu (cooper sulfate), 0.4 mg/kg of I (calcium iodate), and 0.3 mg/kg of Se (sodium selenite).

the only source of amino acids, carbohydrates, and energy in the diets.

Sample Collection, Chemical Analyses, and Calculations

PS distribution analysis was performed at the Kansas State University Swine Nutrition Laboratory (Manhattan, KS) following the method of Kalivoda et al. (2017) method. In brief, an approximately 100 ± 5 g subsample of each ground corn treatment was obtained using a riffle divider and an analytical scale. Weighed subsamples were placed in a sieve shaker (model Ro-Tap RX-29; W. S. Tyler Industrial Group, Mentor, OH) equipped with 13 sieves (U.S. standard sieve numbers 6, 8, 12, 16, 20, 30, 40, 50, 70, 100, 140, 200, and 270) and a pan equipped with sieve agitators (model SSA-58; Gilson Company Inc., Lewis Center, OH), and 0.5 g of dispersion agent. Samples were shaken for 15 min. Geometric mean diameter and geometric standard deviation were calculated according to the ANSI/ASAE S319.2 (American Society of Agricultural and Biological Engineers [ASABE], 1996) standard method for PS analysis. Samples from middle sieve fractions (sieves numbers 20, 30, 40, 50, and 70) were collected for further laboratory analyses.

At the time of mixing, 10 subsamples of each diet were collected and then thoroughly homogenized and carefully subsampled. Fresh fecal samples were obtained twice daily (0930 h and 1630 h) during d 9 to 11 of each test period, placed in pre-labeled plastic bags and immediately frozen at −20 °C for later processing. Once collections were completed, fecal samples were thawed at room temperature, homogenized, dried to constant weight in an oven at 65 °C (Jacobs et al., 2011), and ground in a Wiley mill through a 1-mm screen (Model ED-5; Thomas Scientific Inc., Swedesboro, NJ). Feed and sieve fractions were divided into two subsamples, one ground through a 1-mm screen and the second through a 0.5-mm screen using a Retsch grinder (Model ZM1; Retsch Inc., Newton, PA). All fecal, feed, and sieve fraction samples were kept in plastic bags in desiccator cabinets to maintain constant moisture content until all laboratory assays were completed.

Field-emission scanning electron microscopy was used to capture detailed images of the topography and size of particles of feed at the Roy J. Carter High Resolution Microscopy Facility (Iowa State University, Ames, IA). Samples were mounted on circular aluminum stubs with double-sided carbon tape and coated with platinum to a maximum thickness of 8 nm using a high-resolution sputter coater adapted with a high-resolution thickness controller (HR 208; Cressington Scientific Instruments Ltd, Watford, UK). Samples were examined and photographed with an ultralow-voltage cold-cathode field-emission scanning electron microscope (Hitachi S-4800; Hitachi, Krefeld, Germany) at a voltage of 10.0 kV. Multiple representative pictures of each diet were captured at 50× in low magnification, and images were scaled with the associated software (4800 FE-SEM Hitachi Internal Software; Hitachi).

Chemical composition of sieve fractions, feed, and fecal samples were analyzed at the Monogastric Nutrition Laboratory (Iowa State University, Ames, IA). Assays included dry matter (DM) using a drying oven (method 930.15; AOAC, 2007) and crude protein (CP) as N × 6.25 using the combustion method (Nitrogen Determinator, model TruMac N; Leco Corporation, St. Joseph, MI; method 990.03; AOAC, 2007). The standard for calibration was ethylenediaminetetraacetate (9.57% N; Leco Corporation) and determined to contain 9.58 ± 0.02% N. Acid-hydrolyzed ether extract (AEE) was determined using a SoxCap hydrolyzer (model SC 247) and a Soxtec fat extractor (model 255; Foss, Eden Prairie, MN; method 968; AOAC, 2007). Starch content was determined using the Megazyme total starch assay kit (Wicklow, Ireland; modified method 996.11; AOAC 1996). Acid detergent fiber (ADF) and neutral detergent fiber (NDF) content of feed and fecal samples were determined using an Ankom automated fiber analyzer (model 2000; Macedon, NY; a modified method from Van Soest and Robertson (1979)). Hemicellulose content was determined by subtracting ADF from NDF. Gross energy (GE) was determined using a bomb calorimeter (Model 6200; Parr Instrument Co., Moline, IL). Benzoic acid (6318 kcal GE/kg; Parr Instruments Co.) was used as the standard for calibration and was determined to contain 6323 ± 1.8 kcal GE/kg. TiO_2 in feed and fecal samples was determined colorimetrically using a spectrophotometer according to the method of Leone (1973) (Model Synergy 4; BioTek, Winooski, VT). The apparent total tract digestibility (ATTD) of DM, GE, CP, AEE, NDF, ADF, and hemicellulose was calculated using the following equation (Oresanya et al., 2008):

ATTD, % = {100 − [100 × (% TiO_2 in feed/% TiO_2 in feces) × (concentration of component in feces/concentration of component in feed)]}

Statistical Analysis

Data were analyzed using the following model:

$$y_{ijkl} = \mu + \tau_i + \lambda_j + \theta_k + (\tau\lambda)_{ij} + (\tau\theta)_{ik} + (\lambda\theta)_{jk} + (\tau\lambda\theta)_{ijk} + \delta_l + \varepsilon_{ijk}$$

where y_{ijkl} represents the observed value; μ is the overall mean; τ represents the fixed effect of PS (*i* = 1, 2, 3 [for 300, 500, and 700 µm]); λ represents the fixed effect of GM (*j* = 1, 2 [hammermill and roller mill, respectively]); θ represents the fixed effect of BW category (*k* = 1, 2 [growing period and finishing period, respectively]); τλ represents the interaction effect between PS and GM; τθ represents the interaction effect between PS and BW category; λθ represents the interaction between GM and BW category; τλθ represents the interaction among PS, GM, and BW category; δ represents the random effect of pig; and ϵ is the random error assuming that δ_l is normally distributed with zero mean and an unknown variance [~N (0, σ^2_δ)] and ϵ_{ijk} ~N (0, $\sigma^2\varepsilon$).

The pig was the experimental unit for all analyses. The UNIVARIATE procedure of SAS version 9.3 (SAS Inst., Inc., Cary, NC) was used to verify normality and homogeneity of the residual variance from the reported models. The model was analyzed using the MIXED procedure of SAS. Effects were considered significant with *P*-values ≤ 0.05 and *P*-values between 0.05 and 0.10 were considered trends.

RESULTS

Physical Composition of Corn and Chemical Composition of Experimental Diets

The particles resulting from the grinding showed an expected decrease in size for each PS category (Fig. 1). The mean PS of corn ground with the hammermill (305, 499, and 710 µm) and roller mill (275, 496, and 680 µm) were very close to target (700, 500, and 300 µm; Table 2). The SD of particle ranged from 2.1 to 2.6 for the roller mill and from 2.9 to 3.5 for hammermill; generally speaking, and particularly in the roller-milled corn, the SD seemed to increase with increasing mean PS. On the other hand, the wider distribution of PS observed in the product processed through the hammermill is further revealed by the PS distribution presented in Fig. 2. Despite some small differences in the CP, AEE, starch, and NDF concentrations, the analyzed chemical composition of the experimental diets confirmed the similar composition of the six experimental diets (Table 3).

ATTD of Dietary Components

As expected, finishing pigs had greater ATTD of DM, GE, and N than growing pigs (*P* = 0.02, *P* = 0.01, and *P* <0.01, respectively; Figs. 3A to 5A). The ATTD of DM, GE, and N was similar in pigs fed hammermilled corn across all PS treatments. However, in roller-milled corn, it increased as PS was reduced (*P* < 0.05; Figs. 3B to 5B). These responses were the same in growing and finishing pigs.

The ATTD of AEE in growing pigs was similar between corn ground at 700 and 500 µm, but it increased by further reducing PS to 300 µm (*P* < 0.05; Fig. 6A). In finishing pigs, the ATTD of AEE increased as mean PS decreased from 700 to 300 µm (*P* < 0.05). The ATTD of AEE was similar when feeding hammermilled corn from 700 to 300 µm (Fig. 6B). On the other hand, the ATTD of AEE was similar for corn ground in a roller mill to 700 and 500 µm, but it increased when PS was reduced to 300 µm (*P* < 0.05).

Unexpectedly, the ATTD of NDF and hemicellulose decreased as PS decreased in growing pigs fed hammermilled corn (*P* < 0.05; Table 4), whereas the ATTD of ADF decreased only when corn was ground to 300 µm (*P* < 0.05). In contrast, the ATTD of NDF and ADF increased in growing pigs fed roller-milled corn when it was ground to 300 µm (*P* < 0.05); the ATTD of hemicellulose increased as PS decreased (*P* < 0.05).

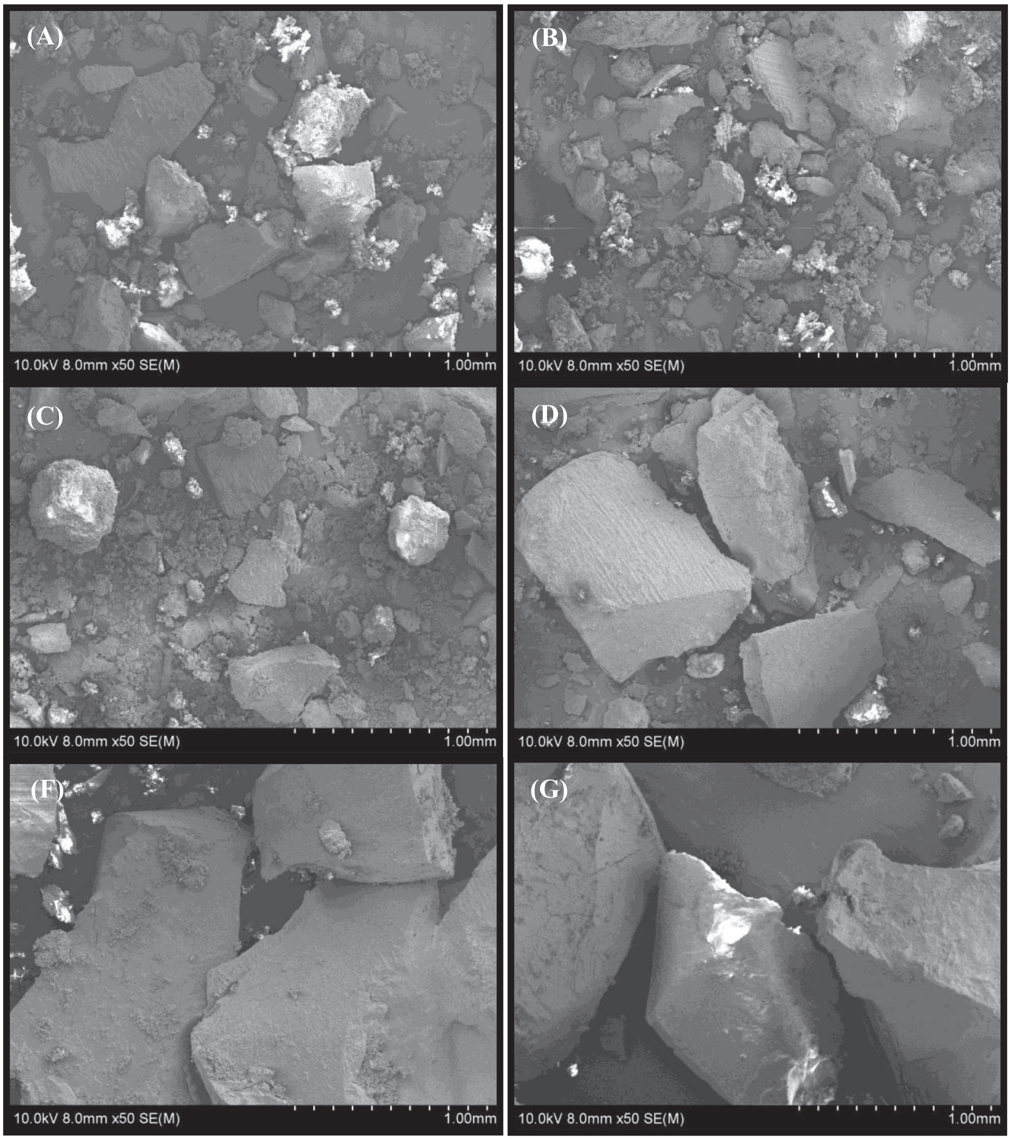

Figure 1. Scanning electron microscopic observation (50×) of ground particles of corn ground to a mean PS of (A) 300 µm with a roller mill, (B) 300 µm with a hammermill, (C) 500 µm with a roller mill, (D) 500 µm with a hammermill, (F) 700 µm with a roller mill, and (G) 700 µm with a hammermill.

Table 2. Geometric mean diameter (d_{gw}) and geometric standard deviation (S_{gw}) of corn ground with a hammermill or a roller mill at three different PSs[1]

	Hammermill			Roller mill		
	Targeted PS, µm			Targeted PS, µm		
Item	300	500	700	300	500	700
d_{gw}, µm	305	499	710	275	496	680
S_{gw}, µm	2.92	3.50	3.42	2.14	2.51	2.64

[1]Variables were determined according to ANSI/ASAE S319.2 (ASABE, 1996) standard method for PS analysis at the Kansas State University Swine Nutrition Laboratory.

In finishing pigs fed hammermilled corn, the ATTD of NDF and hemicellulose was similar across PS. The ATTD of ADF decreased in hammermilled corn ground to 700 µm ($P < 0.05$). On the other hand, the ATTD of NDF, ADF, and hemicellulose decreased when corn was ground to 700 µm using a roller mill ($P < 0.05$).

Chemical Composition of Sieve Fractions

The chemical analysis of the particles retained in the various sieves must be interpreted with great care as there is no replication, so all values are simple means (Table 5). Nonetheless, these data are quite novel and of value in understanding the

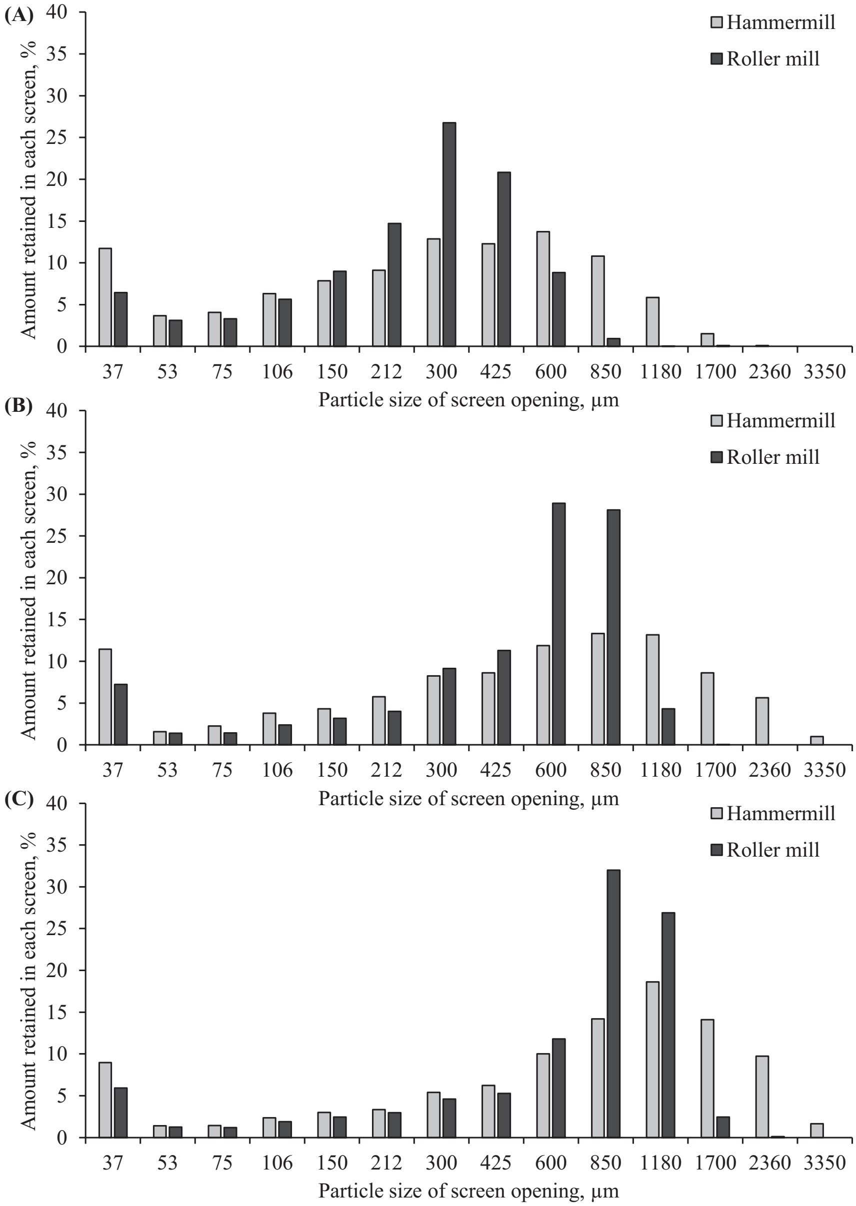

Figure 2. PS distribution, expressed as a percent of the total sample, of corn ground to a mean PS of (A) 300 µm, (B) 500 µm, or (C) 700 µm using a hammermill or a roller mill (*n* = 1 for all samples).

Table 3. Analyzed chemical composition of experimental diets, as-fed basis

	Hammermill			Roller mill		
	Targeted PS, µm			Targeted PS, µm		
Item	300	500	700	300	500	700
DM, %	89.8	89.4	89.4	89.7	89.9	90.2
GE, Mcal/kg	3.73	3.74	3.73	3.70	3.74	3.72
CP, %	8.3	8.2	8.4	8.0	7.8	7.7
AEE, %	2.3	3.2	3.1	2.3	2.3	3.0
Starch, %	60.8	64.3	65.6	60.6	61.6	61.9
ADF, %	2.6	2.6	2.6	2.3	2.7	2.5
Hemicellulose	4.2	4.6	5.4	4.2	4.1	4.1
NDF, %	6.8	7.2	8.0	6.5	6.8	6.6

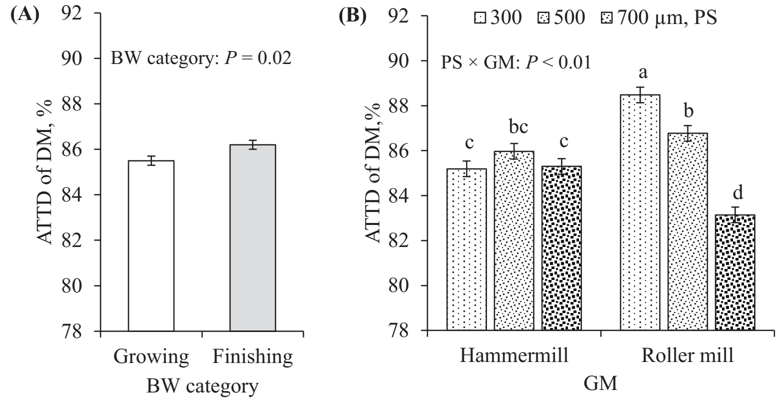

Figure 3. Effects of (A) BW category (growing period, initial average BW = 55 kg; finishing period, initial average BW = 110 kg), and (B) the interaction between mean PS of corn and the GM used on the ATTD of DM. [a–d]Values with differing superscripts denote differences ($P \le 0.05$). No interactions between BW category and PS ($P = 0.52$), BW category and GM ($P = 0.37$), or BW category, PS, and GM ($P = 0.14$).

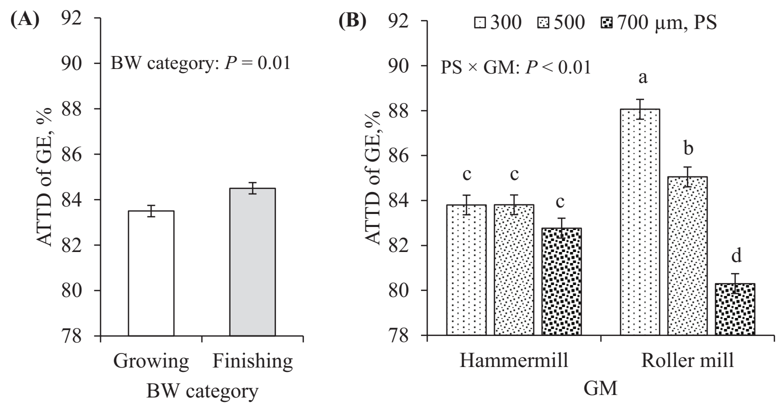

Figure 4. Effects of (A) BW category (growing period, initial average BW = 55 kg; finishing period, initial average BW = 110 kg), and (B) the interaction between mean PS of corn and the GM used on the ATTD of GE. [a–d]Values with differing superscripts denote differences ($P \le 0.05$). No interactions between BW category and PS ($P = 0.34$), BW category and GM ($P = 0.21$), or BW category, PS, and GM ($P = 0.22$).

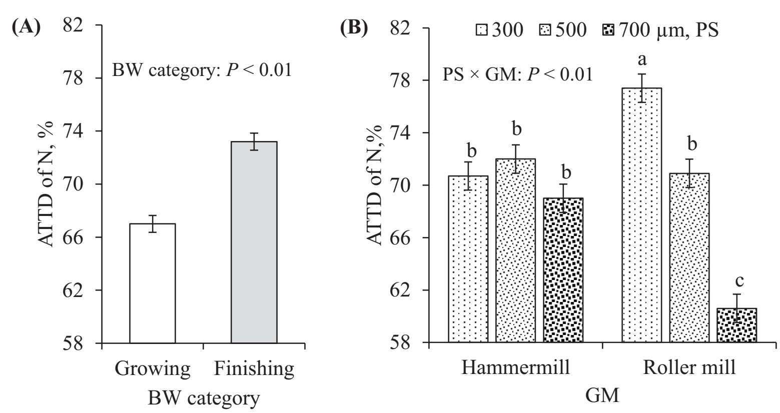

Figure 5. Effects of (A) BW category (growing period, initial average BW = 55 kg; finishing period, initial average BW = 110 kg), and (B) the interaction between mean PS of corn and the GM used on the ATTD of N. [a–c]Values with differing superscripts denote differences ($P \le 0.05$). No interactions between BW category and PS ($P = 0.98$), BW category and GM ($P = 0.19$), or BW category, PS, and GM ($P = 0.11$).

impact of PS reduction in hammermills and roller mills. Overall, there were only what appeared to be two noticeable changes across sieve samples. At 300 µm, the concentration of NDF increased from 4.0% to 64.4% as sieve opening increased, whereas starch decreased from 66.4% to 20.2% as sieve opening increased. At 700 µm, the concentration of starch increased from 55.6% to 65.7% as sieve opening increased. Otherwise, there appeared to be little if any difference in the composition of the sieve fractions across GM, nutrient, and screen size.

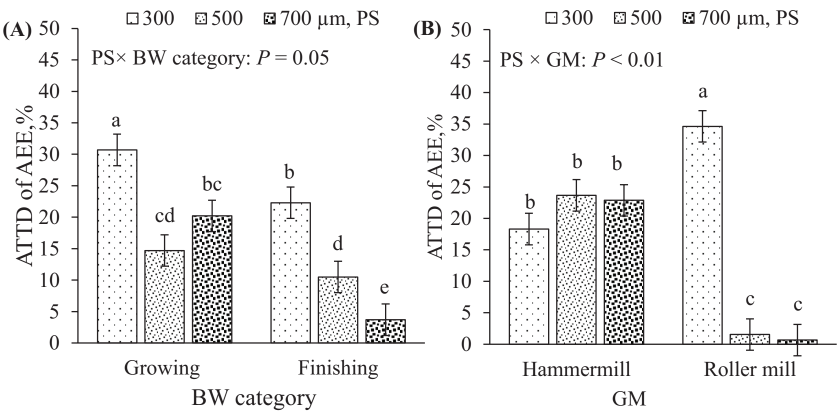

Figure 6. Effects of (A) the interaction between mean PS and BW category (growing period, initial average BW = 55 kg; finishing period, initial average BW = 110 kg), and (B) the interaction between PS of corn and the GM used on the ATTD of AEE. [a–e]Values with differing superscripts denote differences ($P \le 0.05$). No interactions between, BW category and GM ($P = 0.13$), or BW category, PS, and GM ($P = 0.83$).

Table 4. Effect of BW category[1], PS, and GM on the ATTD of fiber components of corn

Item			ATTD, %		
BW category	GM	PS	NDF	ADF	Hemicellulose
Growing	Hammermill	300 µm	32.8[e]	48.3[ef]	23.4[e]
		500 µm	43.7[cd]	54.4[cd]	37.6[cd]
		700 µm	51.6[ab]	57.7[abc]	48.6[ab]
	Roller mill	300 µm	49.5[bc]	57.6[abc]	45.0[bc]
		500 µm	43.6[cd]	58.0[abc]	34.1[d]
		700 µm	32.1[e]	44.9[f]	24.5[e]
Finishing	Hammermill	300 µm	51.5[ab]	54.9[bcd]	49.4[ab]
		500 µm	48.1[bcd]	57.3[abc]	42.8[bcd]
		700 µm	46.8[bcd]	51.3[de]	44.6[bc]
	Roller mill	300 µm	56.5[a]	60.8[ab]	54.2[a]
		500 µm	51.9[ab]	61.0[a]	46.0[abc]
		700 µm	41.1[d]	50.9[def]	35.3[d]
Pooled SEM			2.5	2.1	3.2
Source of variance					
Period			<0.01	0.05	<0.01
GM			0.97	0.22	0.68
PS			0.03	<0.01	0.09
BW category × GM			0.48	0.23	0.87
BW category × PS			0.01	0.27	0.01
GM × PS			<0.01	<0.01	<0.01
BW category × GM × PS			<0.01	0.03	<0.01

[1]BW category (growing period, initial average BW = 55 kg; finishing period, initial average BW = 110 kg).
[a–f]Within a column means with different superscripts significantly differ ($P < 0.050$) between dietary treatments.

DISCUSSION

Reducing mean PS is an important component of feed processing technologies, adopted to maximize the nutritional value of corn. The reduction of mean PS is achieved through grinding, a mechanical method of rupturing the kernel structure into smaller fragments. The intent is to disrupt the original structure, exposing nutrients originally encapsulated within the hull and thus substantially increasing the surface area (Rojas et al., 2016). The resulting smaller particles are believed to be more accessible to digestive processes, specifically enzymatic action such that the digestibility of the dietary components is increased (Giesemann et al., 1990; Wondra et al., 1995).

Although the two methods used to grind corn (roller milling or hammermilling) can achieve a similar mean PS, the resultant products are not the same. For example, the roller mill grinds by both compression and shear. Pairs of corrugated rolls are set a specified distance apart and turn at similar or differential speeds to crack and size the grain, leading to particles of relatively consistent size and

Table 5. Analyzed chemical composition of sample fractions of ground corn retained at each screen opening using either a hammermill or a roller mill, as-is basis[1]

	Corn ground at 300 µm					Corn ground at 500 µm					Corn ground at 700 µm				
	Sieve screen opening[2], µm					Sieve screen opening, µm					Sieve screen opening, µm				
Item	212	300	425	600	850	212	300	425	600	850	212	300	425	600	850
Hammermill															
DM, %	91.4	90.6	89.7	90.1	89.8	91.5	90.3	89.8	89.4	90.2	90.4	89.9	89.7	89.2	88.8
GE, Mcal/kg	4.06	4.04	4.01	4.03	4.05	4.05	4.04	4.06	4.01	4.03	4.06	4.04	3.94	3.93	4.05
CP, %	8.6	8.7	8.7	9.0	9.1	8.4	9.9	8.0	8.7	10.7	8.2	8.5	8.7	9.1	9.2
AEE, %	3.6	3.4	3.4	3.7	4.5	3.3	3.4	3.2	3.6	4.7	3.2	3.1	3.8	3.4	4.5
NDF, %	7.8	9.1	8.9	7.6	8.3	8.0	10.0	10.0	9.4	7.4	8.7	10.9	11.1	10.9	7.6
Starch, %	64.3	58.7	56.7	56.3	67.2	68.3	55.6	56.0	59.9	64.9	64.0	67.3	63.0	57.3	63.5
Roller mill															
DM, %	90.1	89.9	90.0	90.4	92.8	92.1	90.9	89.8	89.2	89.6	90.2	90.4	91.0	89.7	91.1
GE, Mcal/kg	3.95	3.95	4.04	4.15	4.20	4.05	4.04	3.97	3.99	4.06	4.06	4.02	4.05	3.97	4.06
CP, %	8.0	8.7	9.3	10.7	7.8	7.7	7.7	7.7	8.3	9.9	7.9	7.8	8.0	9.3	8.9
AEE, %	3.2	3.7	3.9	6.0	3.6	3.9	3.8	3.3	3.4	5.2	3.8	3.9	3.5	3.2	4.3
NDF, %	4.0	5.0	6.6	15.2	61.4	6.9	7.2	5.6	5.3	9.9	8.9	9.2	7.8	8.3	7.5
Starch, %	66.4	64.7	64.2	53.7	20.2	68.1	62.2	66.0	62.6	61.2	55.6	59.9	64.9	61.9	65.7

[1]Analysis was performed in duplicate (except for NDF which was analyzed in triplicate) from the particles retained in each sieve opening.
[2]Screen sizes: 212, 300, 425, 600, and 850 µm correspond to the U. S. standard sieve numbers 70, 50, 40, 30 and 20, respectively.

shape. Alternatively, hammermills grind by impact; a central rotor spins pivoting hammers that affect the grain, causing it to shatter into particles of relatively inconsistent shapes and sizes that then must either pass through a screen or be affected again until they are small enough to exit the grinding chamber. This leads to variation in such characteristics as geometrical shape, SD, distribution, and chemical composition. All these factors could potentially affect digestibility (Wondra et al. 1995; Patience and Chipman, 2010). Results of this experiment suggest that the ATTD of DM, GE, N, and AEE of corn ground in a roller mill increased as mean PS decreased (from 700 to 300 µm) but no such effect was observed when a hammermill was used. However, it is important to mention that, compared to the roller-milled corn, the digestibility of the hammermilled corn was generally higher at 700 µm, similar at 500 µm, and lower at 300 µm.

In the current experiment, differences in the resulting particles between the two GMs were evident. The hammermill generated particles with greater SD of PS, and a wider PS distribution than the roller mill. There were fewer particles close to the mean, more large particles (>1,000 µm), and more fine particles (37 µm). In addition, the differences in PS distribution between the two mill types has been consistently reported in the literature (Nir et al., 1995; Xu et al., 2015; Vukmirović et al., 2016), including the increase in fine particles when grinding with a hammermill (Nir et al., 1990; Svihus et al., 2004). Therefore, it is possible that the variability in the size of the particles plays a relevant role in digestibility outcomes. In fact, Patience and Chipman (2010) reported decreased digestibility as the SD increased in corn ground in a roller mill to a fixed mean PS of 550 µm. Alternatively, the differences between the two GMs could be the result of the geometrical shape of the ground material. Particles of hammermilled corn have been described as more spherical in shape than roller-milled corn (Reece et al., 1985). This shape can reduce access to digestive enzymes, thereby reducing digestibility (Hancock and Behnke, 2001).

The chemical composition of ground corn was evaluated based on an assumption that smaller particles are able to pass through sieve holes with a progressively reduced diameter (Liu, 2009). Hammermilling showed only minor changes in the chemical composition that coincide with the similar digestibility response across mean PS categories. In contrast, corn ground in a roller mill showed some different nutrient profiles of particles in starch and fiber concentrations at the mean PS of 300 µm. Although not definitive, the nutrient profile of particles may help to explain the digestibility response to PS when the roller mill was used as compared to the hammermill.

Overall, the differences in SD, distribution, shape, and possibly the chemical composition among the particles resulting from the grinding process may be a key factor explaining the digestibility response to decreasing PS (Morel and Cottam, 2007); it may also help to explain the differences between hammermilling and roller milling observed in this experiment. In practice, one method to eliminate the effect of GM on digestibility is the use of a two-stage or a multiple stage grinding system. In fact, Rojas and Stein (2015) achieved a linear increase on the digestibility of energy and starch by grinding corn first in a roller mill and then in a hammermill.

It is well known that the digestibility of most dietary components improves as the pigs age (Noblet and Henry, 1993). This is mainly attributed to the further development of the capability of the gastrointestinal tract (Noblet and van Milgen 2004). However, it was unclear if BW category played a role in the way pigs respond to the PS reduction or to the GM used. This experiment showed that BW category improved the ATTD of DM, GE, and N independent of the mean PS or the GM used. However, the ATTD of AEE was dependent of the BW category. The ATTD of AEE increased as mean PS decreased in finishing pigs but in growing pigs, it was similar at 700 and 500 µm and greater at 300 µm. The difference between growing and finishing pigs is probably the consequence of the influence of intestinal endogenous secretions (Kellner, 2017). In this case, it is possible that greater endogenous losses in finishing pigs may lower apparent digestibility of AEE compared to growing pigs. However, as endogenous secretions were not determined in this experiment, it will be necessary to investigate this effect further.

Fiber digestibility in the current experiment appeared to depend on all three factors evaluated (BW category, GM, and mean PS). The hammermilled corn particles did not seem to be well fermented (digestible) at a lower PS in the growing pig, whereas PS did not seem to matter in the finishing pig. This agrees with Saqui-Salces et al. (2017) who reported similar ATTD of NDF in finishing pigs when mean PS of a corn–soy diet was reduced from 615 to 364 µm in a hammermill. Although no comparable data were found using a roller mill, there appeared to be a consistent increase in fiber digestibility in growing and finishing pigs as PS decreased in this experiment. Therefore, reducing the PS of corn in a roller mill may result in fermentable fiber being more accessible to the intestinal microbiota (Stewart and Slavin, 2009) and thereby increasing apparent fiber digestibility.

In conclusion, reducing mean PS of corn with a roller mill increased digestibility of energy and nutrients; in contrast, there was little to no effect using a hammermill. It is possible that differences in PS distribution, SD, chemical composition, and the shape of the particles resulting from the grinding process explain these differences. Finishing pigs had improved digestibility of DM, GE, and N compared to growing pigs. Except for the digestibility of fat and fiber, BW did not seem to play a role in the way pigs respond to PS.

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