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Project Title and NPB project identification number
#21-104
Interactive effects of pelleting and particle size reduction of corn on net energy and amino acid digestibility in corn-soybean meal diets fed to group-housed pigs

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Industry Summary: The objective of this research was to demonstrate interactive effects of pelleting and reducing particle size of corn on net energy and nutrient digestibility in feeds for growing pigs. Results indicated that pelleting diets increases net energy and digestibility of amino acids, starch, energy, nitrogen, soluble dietary fiber, and fat, but decreases digestibility of calcium and phosphorus in corn-soybean meal based diets fed to growing pigs. Reducing particle size of corn also increases digestibility of amino acids, starch, energy, nitrogen, soluble dietary fiber, and fat. The interactive effects of pelleting and reducing particle size were observed for net energy and digestibility of starch and amino acids that the effects were more pronounced when diets are pelleted. Therefore, pork producers can take advantage of the results from this research when formulating meal or pelleted diets containing different particle size of corn.
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Key Findings:

- Pelleting diets increases ileal digestibility of amino acids and starch.
- Pelleting diets increases total tract digestibility of dry matter, energy, nitrogen, soluble dietary fiber, and fat, but decreases digestibility of calcium and phosphorus.
- Pelleting diets increases concentration of net energy in diets fed to pigs housed in group.
- Reducing particle size of corn increases ileal digestibility of amino acids and starch.
- Reducing particle size of corn increases total tract digestibility of dry matter, energy, nitrogen, soluble dietary fiber, and fat.
- Effects of reducing particle size of corn on the digestibility of starch and amino acids and net energy were more pronounced if particle size of corn was reduced from

700 or 500 μm to 300 μm in meal diets and if particle of corn was reduced from 700 μm to 500 or 300 μm in pelleted diets.

Keywords: amino acids, corn, digestibility, net energy, particle size, pellet, phosphorus

Scientific Abstract: Two experiments were conducted to determine the interactive effects of particle size reduction and pelleting on the apparent ileal digestibility (**AID**) of starch, standardized ileal digestibility (**SID**) of amino acids (**AA**), apparent total tract digestibility (**ATTD**) of fiber, fat, calcium, and phosphorus, and net energy (**NE**) in corn-soybean meal diets fed to pigs. Six corn-soybean meal based diets were arranged by 3 × 2 factorial with 3 particle sizes of corn (i.e., 700, 500, or 300 μm) and 2 diet forms (i.e., meal or pelleted). An N-free diet was also used in Exp. 1. Pigs were allowed ad libitum access to feed and water in Exp. 1 and 2. In Exp. 1, seven pigs (initial weight = 59.30 kg) that were equipped with a T-cannula in the distal ileum were allotted to the 7 diets using a 7 × 7 Latin square design with 7 periods. Ileal digesta were collected for 2 days after 5 days of adaptation. Results indicated that there were no interactions in the AID of starch and the SID of Arg, His, Ile, Trp, and total AA. The interactions were observed for the SID of Leu, Lys, Met, Phe, Thr, and Val ($P < 0.05$). Regardless of particle size, values for the AID of starch and the SID of most AA were greater ($P < 0.05$) in pelleted diets than in meal diets. Regardless of diet form, values for the AID of starch and the SID of most AA were linearly increased ($P < 0.05$) by reducing corn particle size. In Exp. 2, twenty-four pigs (initial weight = 29.52 kg) were allotted to the 6 diets using a 6 × 6 Latin square design with 6 chambers (i.e., 4 pigs/chamber) and 6 periods. Oxygen consumption and CO_2 and CH_4 productions were measured during fed and fasting states and fecal and urine samples were collected. Result indicated that no interactions were observed for the ATTD of P and total dietary fiber (**TDF**) and N retention. The interactions were observed for the ATTD of gross energy (**GE**), Ca, N, soluble dietary fiber (**SDF**), insoluble dietary fiber (**IDF**), and acid hydrolyzed ether extract (**AEE**) and concentration of NE ($P < 0.05$). Regardless of particle size of corn, the ATTD of GE, N, SDF, and AEE, and concentration of NE were greater ($P < 0.05$) and the ATTD of Ca and P was less ($P < 0.05$) in pelleted diets compared with meal diets. The ATTD of TDF and IDF and retention of N were not affected by diet form. Regardless of diet form, the ATTD of GE, N, SDF, and AEE and concentration of NE were linearly increased ($P < 0.05$) by reducing particle size of corn. There were no effects of reducing particle size of corn on the ATTD of Ca, P, IDF, and TDF and retention of N in meal or pelleted diets. In conclusion, the effects of reducing particle size of corn on the digestibility of starch and AA and NE were more pronounced if particle size of corn was reduced from 700 or 500 μm to 300 μm in meal diets and if particle of corn was reduced from 700 to 500 μm or 300 μm in pelleted diets.

Introduction: Particle size reduction in cereal grains often results in an improved digestibility of starch due to increased surface area of grain, which subsequently increases interaction with digestive enzymes (Huang et al., 2015; Rojas and Stein, 2015; Rojas et al., 2016a). Consequently, the apparent ileal digestibility (**AID**) of starch and gross energy (**GE**) increases as particle size is reduced from 865 to 339 μm (Rojas and Stein, 2015). Improvement in the apparent total tract digestibility (**ATTD**) of GE upon particle size reduction has also been demonstrated in corn and a number of other ingredients when fed to weanling or growing-finishing pigs (Lancheros et al., 2020). In contrast to the demonstrated improvement in the AID of starch and the ATTD of GE, the effects of particle size reduction on the digestibility of amino acids (**AA**) in feed ingredients have been inconsistent (Fastinger and Mahan, 2003; Huang et al., 2015; Rojas and Stein, 2015).

Pelleting often results in improved digestibility of GE, which is primarily due to increased gelatinization of starch that occurs when cereal grains are processed in the presence of heat (Lancheros et al., 2020). Pelleting may also improve the digestibility of protein and AA due to increased protein denaturation that occurs when feed ingredients are processed. This allows for the inactivation of anti-nutritional factors and subsequently improved nutritional value of feed ingredients (Svihus and Zimonja, 2011). The digestibility of crude protein and AA is improved in pelleted diets containing corn, wheat, SBM, and DDGS (Lahaye et al., 2008; Rojas et al., 2016b). However, pelleting may also reduce particle size of grain, and it is not known if improvements in nutrient digestibility obtained by reducing particle size of grain and those reduced by pelleting are additive or if there are interactions between particle size reduction and pelleting.

Prediction equations for NE in diets fed to pigs based on chemical composition are widely used (Noblet et al., 1994; NRC, 2012). However, the equations were developed without considering feed processing including pelleting or different particle sizes. These equations may, therefore, not be applicable to pelleted diets containing ingredients with different particle size, but research to verify this assumption has not been published.

Objectives: The objective was to determine the interactive effects of particle size reduction and pelleting on ileal digestibility of amino acids and starch, total tract digestibility of fiber, fat, calcium, and phosphorus, and net energy in corn-soybean meal diets fed to pigs.

Materials & Methods: Two experiments were conducted to determine the interactive effects of particle size of corn and pelleting diets.

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocol for this experiment. Pigs were the offspring of Line 359 boars and Camborough females (Pig Improvement Company, Hendersonville, TN, USA). One source of yellow corn was ground to 3 different particle sizes using a hammermill (i.e., 700, 500, and 300 µm) before included in all diets.

Diet

Six diets were formulated based on corn and soybean meal and fed to pigs in Exp. 1 and 2 (Table 1). Dietary treatments were arranged by 3 × 2 factorial with 3 particle sizes of corn and 2 diet forms (i.e., meal or pelleted). The 3 diets were pelleted with an average production rate of 15.3 kg/min; conditioning temperature was 83.0 °C and pelleting temperature was 88.5 °C. An N-free diet was used to determine basal endogenous losses of crude protein (**CP**) and AA in Exp. 1 and thus there were a total of 7 diets in Exp. 1. All diets contained TiO_2 as an index.

Exp. 1: SID of AA

Animal, housing, and sample collection A total of 7 growing pigs (initial BW: 59.30 kg; SD = 2.77) that were equipped with a T-cannula in the distal ileum were allotted to the dietary treatments using a 7 × 7 Latin square design with 7 pigs, 7 treatments, and 7 periods. Therefore, there were 7 replicate pigs per treatments. Pigs were placed in pens that had a feeder, a drinking nipple, and fully slatted floors. Pigs were fed at libitum. Water was available at all times.

Each experimental period lasted 7 days. The initial 5 days of each period were considered an adaptation period. Ileal digesta were collected on day 6 and 7 for 8 hours. In short, the cannulas were opened and a plastic bag (7.6 × 20.3 cm) was attached to the cannula barrel using a cable tie and digesta flowing into the bag were collected. Bags were removed every 30 min and replaced with a new one. All samples were stored at −20 °C as soon as they were collected. At the conclusion of experiment, ileal digesta samples were thawed, mixed within animal and diet, and a sub-sample was collected for analysis. Digesta samples were lyophilized and finely ground through using a coffee grinder.

Exp. 2: NE in diets and the ATTD of fiber, fat, Ca, and P

Animal, housing, and sample collection A total of 24 growing pigs (initial BW: 29.52 kg; SD = 1.40) were allotted to the 6 diets using a 6 × 6 Latin square design with 6 chambers and 6 periods. Therefore, there were 6 replicate chambers per diet. Pigs were housed in a group of 4 pigs per calorimetric chamber. Each chamber was equipped with a stainless steel wet-dry feeder, and an auxiliary nipple waterer was in each chamber to ensure free access to water. Each chamber was equipped with a slatted floor, 4 stainless steel fecal screens, and 2 urine pans for total, but separate, collection of fecal and urine materials. The temperature and relative humidity inside the chambers were controlled by a temperature and humidity control unit, and the air velocity was controlled using an airflow meter (AccuValve; Accutrol, LLC, Danbury, CT, USA).

Throughout the study, pigs were fed ad libitum. Diets were fed for 13 d, where the initial 7 d were considered the adaptation period to the diet. At 0700 h on d 8, the gas analyzers started measuring O_2 consumption and CO_2 and CH_4 productions. Fecal and urine samples were also collected from d 8 to d 13. At 0700 h on d 14, pigs were deprived of feed for 36 h. This time was considered as a fasting period to determine fasting heat production (**FHP**). The first 24 h of fasting was considered as the time the animals digest and metabolize the remaining feed in the intestinal tract to produce energy, whereas the last 12 h gas consumption and production were measured and urine samples were collected, which was considered the actual period where animals mobilized endogenous nutrients to produce energy. Therefore, each period lasted 14.5 d.

During the collection period and for avoiding N loss in the urine, 50 ml of 6*N* HCl were added to each urine pan every day, for a total of 100 ml of 6*N* HCl per chamber. Chambers were open every day to check feeders, and for the collection of fecal and urine materials from the chambers. Data from the gas analyzers obtained during the period that the chambers were open and until they reached the condition set by the temperature and humidity control unit were disregarded for the final calculation of heat production. Fecal samples and 5% of the urine samples were stored at −20 °C immediately after collection.

Urine samples were thawed and mixed within chamber and diet, and a sub-sample was lyophilized. Fecal samples were thawed and mixed within chamber and diet, and then dried in a 50 °C forced air drying oven. Fecal samples were ground through a 1-mm screen using a Wiley mill (Model 4; Thomas Scientific, Swedesboro, NJ, USA). Urine subsamples were mixed and 10 mL of urine was dripped onto cotton balls that are placed in a plastic bag and lyophilized (Kim et al., 2009).

Chemical analysis
Diets and ground fecal samples and lyophilized urine samples from Exp. 2 were analyzed for GE using bomb calorimetry (Model 6400; Parr Instruments, Moline, IL, USA). Diet, ileal digesta samples from Exp. 1, and fecal samples from Exp. 2 were analyzed for dry matter (**DM**; method 930.15; AOAC Int., 2019) and ash in diet samples was analyzed (method 942.05; AOAC Int., 2019). Nitrogen in diet and fecal samples from Exp. 2 were determined using a LECO FP628 Nitrogen Analyzer (LECO Corp., Saint Joseph, MI; AOAC Int., 2019; method 990.03) and CP was calculated as analyzed N × 6.25. However, N in urine samples from Exp. 2 was determined using a Kjeltec 8400 apparatus (Method 984.13; AOAC Int., 2019; FOSS, Eden Prairie, MN, USA). Acid hydrolyzed ether extract (**AEE**) in diet and fecal samples from Exp. 2 were analyzed by acid-hydrolysis using 3*N* HCl (AnkomHCl, Ankom Technology, Macedon, NY, USA) followed by crude fat extraction using petroleum ether (AnkomXT15, Ankom Technology, Macedon, NY, USA). Amino acids in diets and ileal digesta samples from Exp. 1 were analyzed on a Hitachi Amino Acid Analyzer, Model No. L8800 (Hitachi High Technologies America, Inc; Pleasanton, CA, USA). Diet and fecal samples from Exp. 2 were analyzed for insoluble dietary fiber (**IDF**) and soluble dietary fiber (**SDF**) using the Ankom Dietary Fiber Analyzer (Ankom Technology, Macedon, NY, USA; method 991.43, AOAC Int., 2019). Total dietary fiber (**TDF**) was calculated as the sum of concentrations of SDF and IDF. Diet and fecal samples from Exp. 2 were analyzed for Ca and P (method 985.01 A, B, and C; AOAC Int., 2019) using inductively coupled plasma-optical emission spectrometry (ICP-OES; Avio 200, PerkinElmer, Waltham, MA, USA). Sample preparation included dry ashing at 600°C for 4 h (method 942.05; AOAC Int., 2019) and wet digestion with nitric acids (method 3050 B; U.S. Environmental Protection Agency, 2000). Diet and ileal digesta samples from pigs fed the 6 corn-soybean meal diets (but not digesta from pigs fed the N-free diet) in Exp. 1 were analyzed for starch using the glucoamylase procedure (method 979.10; AOAC Int., 2007). Titanium in diet and ileal digesta samples Exp. 1 was determined following the procedure of Myers et al. (2004). The particle size of corn and meal diets was determined (ASABE, 2008; De Jong et al., 2016b) and standard deviation of the particle size was also calculated.

Calculations
Exp. 1: SID of AA The basal endogenous losses of CP and AA were calculated using the analyzed CP, AA, and Ti concentrations in ileal digesta samples from pigs fed the N-free diet and Ti in the N-free diet as previously described (Stein et al., 2007). Apparent ileal digestibility (**AID**) was calculated using the analyzed CP, AA, starch, and Ti concentrations in the diets and ileal digesta samples, and the SID of CP and AA was calculated by correcting the AID values for basal endogenous losses of CP and AA (Stein et al., 2007).
Exp. 2: NE in diets and the ATTD of fiber, fat, Ca, and P The ATTD of GE, DM, SDF, IDF, TDF, AEE, Ca, and P and was calculated for each diet, and concentrations of digestible energy (**DE**) and metabolizable energy (**ME**) in each diet were calculated as well (NRC, 2012). Nitrogen intake, nitrogen excretions, and the ATTD and retention of N were also calculated.

For NE, the concentrations of O_2, CO_2, and CH_4 were averaged within the collection period and the last 12 h of the fasting period. Total heat production (**THP**) from pigs fed diets during the collection period was calculated using the following equation (Brouwer, 1965):

$$\text{THP, kcal} = [(3.866 \times O_2 + 1.200 \times CO_2 - 0.518 \times CH_4 - 1.431 \times \text{Urine N})],$$

where O_2, CO_2, and CH_4 were expressed as *l*, and urine N was expressed as g. The FHP from pigs fed during the fasting period was calculated as for the THP. Heat increment was calculated by subtracting FHP from THP and concentrations of NE was then calculated (modified from NRC, 2012):

$$\text{NE, kcal/kg} = \text{ME} - (\text{THP} - \text{FHP})/\text{feed intake},$$

where ME is in kcal/kg, THP and FHP are in kcal, and feed intake is in kg.

Statistical analysis
Homogeneity of the variances and normality were confirmed and data were analyzed using the PROC MIXED in SAS. The statistical model included diet as the fixed effect and chamber and period as the random effects. Contrast statements were used to test the diet form, linear effects of particle size, and the interaction between diet form and particle size. Mean values were calculated using the LSMeans statement and means will be separated using PDIFF option with Tukey's adjustment if the model is significant. Pig in Exp. 1 and calorimeter chamber in Exp. 2 were the experimental unit, respectively. Results were considered significant at $P < 0.05$ and considered a trend at $P < 0.10$.

Results: Pigs remained healthy during the experiment and very few feed refusals were observed.

Exp. 1: SID of AA
Results from this experiment indicated that the AID of DM was not affected by diet form or particle size of corn (Table 3). There was no interaction between diet form and particle size of corn in the AID of starch and the AID of CP. The AID of starch and the AID of CP were greater ($P < 0.05$) if pigs were fed pelleted form compared with meal diets and were linearly increased ($P < 0.05$) as the particle size of corn was reduced from 700 to 300 µm. No interactions between diet form and particle size of corn were observed for the AID of Arg, His, Ile, Thr, Trp, Asp, Glu, Gly, Pro, and total AA. The AID of Leu, Lys, Ala, Ser, and Tyr was increased by reducing particle size of corn, but the effect was greater in pelleted diets than in meal diets (interaction; $P < 0.05$). The AID of Phe and Val in meal diets was not affected by reducing particle size of corn, but the AID values in pellet diets were increased by reducing particle size of corn (interaction; $P < 0.05$). The AID of Met and Cys was increased by reducing particle size of corn, but the effect was greater in meal diets than in pelleted diets (interaction; $P < 0.05$). Regardless of particle size, values for the AID of starch, CP, indispensable AA, and most dispensable AA except for Gly and Pro were greater ($P < 0.05$) if pigs were fed diets in pelleted form than in meal form. Regardless of diet form, values for the AID of starch, CP, most indispensable AA except for Trp, and dispensable AA were linearly increased ($P < 0.05$) by reducing particle size of corn from 700 to 500 to 300 µm.

There was no interaction between diet form and particle size of corn in the SID of Arg, His, Ile, Trp, Asp, Glu, Gly, Pro, and total AA (Table 4). The SID of CP, Lys, Phe, and Val in meal diets was not affected by particle size of corn, but values for the SID were linearly increased by reducing particle size of corn in pelleted diets (interaction; *P*

< 0.05). The SID of Leu, Thr, Ala, Ser, and Try was increased by reducing particle size of corn, but the effect of particle size was greater in pelleted diets compared with meal diets (interaction; $P < 0.05$).

Regardless of particle size, values for the SID of CP, indispensable AA, and most dispensable AA except for Gly and Pro were greater ($P < 0.05$) if pigs were fed diets in pelleted form than in meal form. Regardless of diet form, values for the SID of CP, most indispensable AA except for Trp, and most dispensable AA except Gly and Pro were linearly increased ($P < 0.05$) by reducing particle size of corn from 700 to 500 to 300 µm.

Exp. 2: NE in diets and the ATTD of fiber, fat, Ca, and P

No interactions between diet form and particle size of corn were observed for feed intake and GE intake of pigs, GE in urine, urine GE output, ME intake, THP, FHP, retained energy, respiratory quotient for fasted status, ME to DE, and NE to ME (Table 5). Weight of orts, the ATTD of DM, and the ATTD of GE were increased by reducing particle size of corn from 700 to 300 µm if pigs were fed diets in meal form, but weight of orts was not affected by particle size of corn in pelleted diets (interaction; $P < 0.05$). Weight of feces and fecal GE output were reduced by reducing particle size of corn in diets, but the effects were greater in meal diets than in pelleted diets (interaction; $P < 0.05$). Concentrations of DE, ME, and NE were increased by reducing particle size of corn, but the effects were greater in meal diets than in pelleted diets (interaction; $P < 0.05$). Regardless of particle size of corn, the ATTD of DM and GE, concentrations of DE, ME, and NE, and ME to DE were greater ($P < 0.01$) in pelleted diets compared with meal diets. Regardless of diet form, the ATTD of DM and GE and concentrations of DE, ME, and NE were linearly increased ($P < 0.05$) by reducing particle size of corn.

No interaction between diet form and particle size was observed for intake of Ca and intake of Ca was not affected by diet form or particle size (Table 6). Concentration of Ca in feces and Ca excretion in feces from pigs were increased by reducing particle size of corn, but the magnitude was greater in meal diets compared with pelleted diets (interaction; $P < 0.05$). The ATTD of Ca was reduced by reducing particle size of corn, but the effect was greater in meal diets than in pelleted diets (interaction; $P = 0.004$). Regardless of particle size of corn, Ca excretion in feces was less ($P = 0.001$) and absorbed Ca was greater ($P = 0.001$) in meal diets compared with pelleted diets, which resulted in greater ($P < 0.001$) values for the ATTD of Ca in meal diets than in pelleted diets. There were no effects of reducing particle size of corn on the ATTD of Ca in meal or pelleted diets.

No interactions between diet form and particle size were observed for intake of P, P excretion in feces, absorbed P, and the ATTD of P. Regardless of particle size of corn, fecal P excretion tended to be greater ($P = 0.076$) in pelleted diets, which resulted in greater P absorption ($P = 0.032$) and ATTD of P ($P = 0.037$) in meal diets than in pelleted diets. There were no effects of reducing particle size of corn on the ATTD of P in meal or pelleted diets.

No interactions between diet form and particle size were observed for N intake, absorbed N, N excretion in urine, and N retention. Fecal N excretion was reduced and the ATTD of N was increased by reducing particle size of corn, but the effect was greater in meal diets than in pelleted diets (interaction; $P < 0.05$). Regardless of particle size of corn, fecal N excretion was greater ($P = 0.001$) in meal diets, which resulted in greater ATTD of N ($P = 0.002$) in pelleted diets than in meal diets. However, different diet form did not affect N retention. Regardless of diet form, the ATTD of N was linearly increased ($P = 0.031$) by reducing particle size of corn. There were no effects of reducing particle size of corn on retention of N in meal or pelleted diets.

There was no interaction between diet form and particle size in TDF intake, TDF excretion in feces, absorbed TDF, and the ATTD of TDF and these parameters were not affected by diet form or particle size of corn. Intake of SDF, absorbed SDF, and the ATTD of SDF were increased by reducing particle size of corn in both meal and pelleted diets, but the effects were greater if pigs were fed pelleted diets than if pigs were fed meal diets (interactions; $P < 0.001$). Regardless of particle size of corn, SDF intake, absorbed SDF, and the ATTD of SDF were greater ($P < 0.001$) in pelleted diets than in meal diets. Regardless of diet form, SDF intake, absorbed SDF, and the ATTD of SDF were linearly increased ($P < 0.05$) by reducing particle size of corn from 700 to 300 µm. There was no interaction between diet form and particle size in the ATTD of IDF. Excretion of IDF in feces, absorbed IDF, and the ATTD of IDF were not affected by diet form or particle size of corn.

Intake of AEE in meal diet containing 500 µm corn was less than in the pelleted diet containing 500 µm corn, but AEE intake was not different between meal and pelleted diets containing 700 or 300 µm corn (interaction; $P = 0.006$). Excretion of AEE in feces was decreased and the ATTD of AEE was increased by reducing particle size of corn in meal diets, but no difference was observed among pelleted diets (interaction; $P < 0.001$). Regardless of particle size of corn, AEE excretion was greater ($P < 0.05$) and AEE intake, absorbed AEE, and the ATTD of AEE were less in meal diets compared with pelleted diets. In both meal and pelleted diets, intake of AEE was not affected by particle size of corn, but AEE excretion in feces was linearly decreased ($P = 0.002$), absorbed AEE tended to be increased ($P = 0.053$), and the ATTD of AEE was increased ($P < 0.001$) by reducing particle size of corn in pelleted and meal diets.

Discussion:

The analyzed concentrations of CP, AA, GE, TDF, SDF, IDF, and AEE in diets and values for the SID of AA and concentrations of DE and ME in meal diet containing 700 µm were in agreement with calculated values (NRC, 2012). Concentration of NE in diets, THP, FHP, and ME to NE were greater compared with expected values (Noblet, 1994; NRC, 2012; Kim et al., 2018; Lyu et al., 2022). Total heat production includes heat productions from maintenance, heat increment, activity, and maintaining body temperature (NRC, 2012). The greater THP can be explained by the fact that pigs were fed ad libitum in this experiment whereas pigs were limit fed limit in the previous experiments. It is also possible that pigs were group-housed in a pen where most physical activities were possible whereas previous experiments only used individual indirect calorimeters that allow a minimal activity of pigs. The increased FHP by pigs resulted in increased NE in diets and thus increased ME to NE. As explained for THP, increased activity of pigs may contribute to the increased FHP because pigs have more space for extra activities in the indirect calorimeter chambers. Fasting heat production can also be affected by previous intake of feeds because increased intakes of energy and protein can increase weight of gastrointestinal tract and liver, which utilize as much as 30% of FHP (Koong et al., 1983; Baldwin, 1995; Critser et al., 1995; NRC, 2012). It is possible that pigs produce more heat during the fasting period because pigs were fed ad libitum previously.

Measured particle size of corn used in each diet and meal diets agreed with expected values. Particle size of meal diets was slightly different than particle size of each corn because all diets contained other feed ingredients with different particle sizes. Corn for pig diets in the US is usually milled to particle size close to 700 µm (Wondra et al., 1995; Nemechek et al., 2016; Vukmirović; 2017; Lancheros et al., 2020), which was the reason 700 µm corn was used as the coarsest grain.

Pelleting is a process that moisture, heat, and pressure are applied to feeds. Pelleting is used to reduce segregation of feed ingredients, increase bulk density, improve handling and transportation, reduce dust and feed wastage of pigs, and improve palatability (Chae and Han, 1998; de Jong et al., 2016a). The observations that the digestibility of starch, CP, AA, GE, N, and fat, and concentrations of DE and ME in diets were increased by pelleting agreed with previous data (Wondra et al., 1995; Lahaye et al., 2007; Rojas et al., 2016; Chassé et al., 2021). The increases in the AID of starch and the SID of CP and AA can be explained by the fact that in the presence of heat gelatinization of starch and denaturation of proteins are increased, and antinutritional factors are inactivated (Lancheros et al., 2020). The observation that the SID of CP and AA was increased in pelleted diets compared with meal diets also indicated that there was no heat damage of protein during the pelleting process.

Even though the ATTD of SDF was increased by pelleting, the ATTD of IDF, which is the majority of TDF, was not affected by pelleting. This indicates that the increased digestibility of starch, fat, CP, and AA increased the ATTD of GE and thus increased concentrations of energy in diets. There are limited data that demonstrate the effects of pelleting on NE in diets, but the results from this experiment indicated that pelleting diets increased concentration of NE in diets fed to group-housed pigs. It seems that the increments in the ATTD of GE and metabolizability of DE (i.e., ME to DE) contributed to the increment in NE in diets fed to pigs because NE to ME was not affected by pelleting.

The observation that the ATTD of Ca and P was greater in diets that are in meal form compared with pelleted form was not in agreement with previous data that demonstrated no effects of pelleting on the ATTD of Ca and P (Yang et al., 2017; Hong and Kim, 2021). In both experiments, phytase was used in diets and this may bring confounding effects. However, data from Jongbloed and Kemme (1990) indicated that there were no effects of pelleting on the ATTD of Ca and P in diets containing no phytase. It is not clear why the ATTD of Ca and P in pelleted diets was decreased, but it is possible that the greater surface area of feed particles in meal diets may help the digestion and absorption of dietary Ca and P compared with pelleted diets.

The surface area is increased by reducing particle size of feed ingredients, which allows the feed particles to interact more with digestive enzymes in the intestinal tract of pigs compared with coarse particles (Lyu et al., 2020). Therefore, digestibility of nutrients and energy may be increased by reducing particle size. In this experiment, the ileal digestibility of CP and AA was increased by reducing particle size of corn, but this was not observed in the previous experiments (Fastinger and Mahan, 2003; Rojas and Stein, 2015). However, lupin experiment indicated that the AID of AA in lupins was increased by reducing particle size (Kim et al., 2009) and this was in agreement with data from this experiment.

The observations that the AID of starch, the ATTD of GE and fat, and concentrations of DE and ME in diets were increased by reducing particle size of corn agreed with previous data (Wondra et al., 1995; Rojas and Stein, 2015; Lancheros et al., 2020; Lyu et al., 2020; Ma et al., 2021). There were no experiments to demonstrate the effects of reducing particle size of corn on NE in diets fed to pigs, but previous experiment indicated that reducing particle size of oat increased NE in diet (Koo and Nyachoti, 2021). It was the ATTD of GE that was mostly affected by reducing particle size of corn, which contributed to the increment in concentrations of DE, ME, and NE in diets fed to pigs. Therefore, this indicates that reduction in particle size of corn improves digestion and absorption rather than retention of energy.

The observation that the ATTD of P was not affected by different particle size of corn was in agreement with previous data (Rojas and Stein 2015). The observation that the ATTD of Ca in diets was decreased by reducing particle size of corn was in agreement with oat data (Koo and Nyachoti, 2021). With the fact that corn has Ca close to 0% it is difficult to clearly explain this observation, but it is possible that reduced particle size of corn contributes to increases in the interaction between dietary Ca and phytate that forms undigestible Ca-phytate complex (Stein et al., 2016). However, more research is needed to demonstrate the hypothesis.

It was observed that the ATTD of TDF and IDF was not affected by reducing particle size of corn. In contrast to the well-demonstrated improvement in digestibility of starch and energy, the effects of reducing particle size on digestibility of fiber have been inconsistent. The ATTD of neutral detergent fiber (**NDF**) and acid detergent fiber (**ADF**) was the greatest if particle size of corn was approximately 600 µm then the values were decreased if particle size is increased or reduced (Lyu et al., 2020; Ma et al. 2021). The ATTD of NDF and ADF was increased if whole diets were ground to fine particles (Saqui-Salces et al., 2017), but the ATTD of NDF and ADF was decreased by reducing particle size of corn (Acosta et al., 2020). The ATTD of SDF was increased by reducing particle size of corn, and this was in agreement with previous data demonstrating that the ATTD of hemicellulose was increased by particle size reduction (Acosta et al., 2020). It seems that reducing particle size helped soluble fiber be more fermented because the increased surface area allowed the microbes in the intestine of pigs to get more access to the substrates (Stewart and Slavin, 2009).

The effects of reducing particle size of corn on the AID of starch, the SID of AA, and concentrations of DE, ME, and NE were more pronounced if particle size of corn was reduced from 700 or 500 µm to 300 µm in meal diets and if particle of corn was reduced from 700 to 500 µm or 300 µm in pelleted diets. In addition, the effects of reducing corn particle size on the ATTD of AEE were only observed if diets were in meal form. These observations indicated that there are interactions between diet form and reducing corn particle size. The interactions that the effects of particle size reduction differed depending on diet form can be explained by frictional force that is applied to feed particles during pelleting process, which results in an additional reduction of feed particle size (Vukmirović et al., 2017). It is thus likely that reducing particles resulted in the synergetic effects with pelleting.

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Table 1. Ingredient composition of experimental diets, as-fed basis

Item, %	Diet form	Meal			Pellet		
	Corn particle size, µm	700	500	300	700	500	300
Ground corn, 700 µm		78.100	-	-	78.100	-	-
Ground corn, 500 µm		-	78.100	-	-	78.100	-
Ground corn, 300 µm		-	-	78.100	-	-	78.100
Soybean meal, 48% crude protein		17.150	17.150	17.150	17.150	17.150	17.150
Soybean oil		1.500	1.500	1.500	1.500	1.500	1.500
Dicalcium phosphate		0.891	0.891	0.891	0.891	0.891	0.891
Ground limestone		0.700	0.700	0.700	0.700	0.700	0.700
L-Lys·HCl, 78.8% Lys		0.272	0.272	0.272	0.272	0.272	0.272
DL-Met, 99% Met		0.024	0.024	0.024	0.024	0.024	0.024
L-Thr, 99% Thr		0.063	0.063	0.063	0.063	0.063	0.063
Sodium chloride		0.400	0.400	0.400	0.400	0.400	0.400
Titanium dioxide		0.400	0.400	0.400	0.400	0.400	0.400
Vitamin-mineral premix[1]		0.500	0.500	0.500	0.500	0.500	0.500

[1]The vitamin-micromineral premix will provide the following quantities of vitamins and micro minerals per kg of complete diet: vitamin A as retinyl acetate, 11,150 IU; vitamin D_3 as cholecalciferol, 2,210 IU; vitamin E as selenium yeast, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.42 mg; thiamin as thiamine mononitrate, 1.10 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 1.00 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.6 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 125 mg as iron sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese hydroxychloride; Se, 0.30 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc hydroxychloride.

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

Item, % Diet form	Meal			Pellet		
Corn particle size, µm	700	500	300	700	500	300
Dry matter	89.51	89.51	89.44	90.12	90.55	89.92
Crude protein	13.46	13.06	12.90	12.30	12.77	13.20
Lys to crude protein						
Acid hydrolyzed ether extract	4.48	4.43	4.57	5.07	5.16	5.10
Ash	4.20	4.16	4.11	4.00	4.08	4.07
Gross energy, kcal/kg	3,920	3,876	3,917	3,951	3,976	3,958
Total dietary fiber	10.9	9.1	10.1	10.5	9.7	10.5
Soluble dietary fiber	0.3	0.6	0.4	0.7	0.5	1.0
Insoluble dietary fiber	10.6	8.5	9.7	9.8	9.2	9.5
Starch	48.0	50.4	48.6	49.4	48.7	48.0
Ca	0.58	0.59	0.56	0.54	0.53	0.55
P	0.49	0.45	0.48	0.45	0.46	0.46
Diet particle size, Dgw (µm)	704	557	394	-	-	-
Standard deviation, Sgw	2.36	2.47	2.23	-	-	-
Corn particle size, Dgw (µm)	685	526	320	685	526	320
Standard deviation, Sgw	2.61	2.37	2.20	2.61	2.37	2.20
Indispensable amino acids						
Arg	0.91	0.86	0.98	0.87	0.94	0.95
His	0.39	0.38	0.42	0.38	0.41	0.42
Ile	0.63	0.60	0.68	0.59	0.63	0.65
Leu	1.37	1.35	1.45	1.36	1.42	1.45
Lys	0.97	0.87	1.02	0.93	0.99	1.01
Met	0.26	0.24	0.31	0.25	0.28	0.29
Phe	0.74	0.71	0.79	0.72	0.76	0.77
Thr	0.60	0.56	0.62	0.58	0.62	0.62
Trp	0.13	0.12	0.12	0.13	0.14	0.13
Val	0.72	0.68	0.72	0.68	0.72	0.75
Total	6.72	6.37	7.11	6.49	6.91	7.04
Dispensable amino acids						
Ala	0.81	0.79	0.85	0.80	0.84	0.85
Asp	1.43	1.32	1.54	1.33	1.45	1.47
Cys	0.25	0.25	0.29	0.25	0.28	0.28
Glu	2.63	2.52	2.81	2.53	2.68	2.73
Gly	0.61	0.57	0.65	0.58	0.62	0.63
Pro	0.93	0.93	1.00	0.95	0.97	0.98
Ser	0.63	0.59	0.66	0.61	0.65	0.66
Tyr	0.51	0.49	0.54	0.50	0.53	0.53
Total	7.80	7.46	8.34	7.55	8.02	8.13
Total amino acids	14.77	14.11	15.65	14.33	15.15	15.44

Table 3. Effects of diet form and particle size of corn on apparent ileal digestibility of dry matter, starch, crude protein, and amino acids in diets fed to growing pigs[1]

Item, %	Diet form	Meal			Pellet				Contrast *P*-value		
	Corn particle size, µm	700	500	300	700	500	300	SEM	Diet form	Particle size[2]	Interaction
Dry matter		72.08	74.04	73.72	73.52	75.44	75.29	1.34	0.131	0.152	0.203
Starch		94.59	94.99	97.90	96.93	96.04	97.89	0.73	0.029	0.001	0.063
Crude protein		69.21	70.77	69.92	69.44	72.65	74.73	1.87	0.042	0.032	0.068
Indispensable amino acids											
Arg		85.30	85.15	86.12	85.18	87.66	88.40	1.01	0.009	0.006	0.118
His		80.04	80.70	82.13	80.77	83.22	83.99	1.14	0.021	0.004	0.139
Ile		77.17	77.54	79.34	77.51	80.33	82.42	1.41	0.029	0.004	0.130
Leu		80.22	81.45	82.55	81.84	83.97	85.62	1.14	0.002	0.001	0.010
Lys		82.46	81.87	84.03	83.82	85.06	86.75	1.11	0.001	0.012	0.021
Met		83.39	83.51	87.45	86.27	88.08	89.97	0.96	< 0.001	< 0.001	0.001
Phe		79.20	79.70	80.96	80.09	82.86	84.23	1.22	0.004	0.005	0.038
Thr		70.90	71.38	73.55	72.81	75.53	76.61	1.49	0.005	0.013	0.051
Trp		77.93	77.06	77.59	79.82	80.91	79.68	1.38	0.010	0.834	0.093
Val		73.59	73.93	74.92	74.96	77.70	80.09	1.53	0.003	0.016	0.015
Total		79.36	79.71	81.32	80.52	82.82	84.30	1.18	0.003	0.004	0.028
Dispensable amino acids											
Ala		74.65	76.00	78.27	78.08	79.57	82.24	1.39	< 0.001	0.001	0.001
Asp		76.56	76.45	79.14	76.85	79.88	80.83	1.32	0.031	0.002	0.314
Cys		66.73	68.55	74.22	70.83	75.40	74.88	1.55	< 0.001	< 0.001	0.039
Glu		82.56	82.63	84.15	83.40	85.78	85.82	1.09	0.002	0.007	0.076
Gly		59.04	55.81	62.46	55.75	61.02	62.89	2.77	0.663	0.023	0.520
Pro		70.58	69.04	74.85	63.35	66.96	71.53	5.22	0.079	0.037	0.073
Ser		76.82	77.34	79.05	78.39	81.15	82.39	1.23	0.001	0.002	0.011
Tyr		79.03	79.75	81.62	81.20	83.44	84.16	1.07	0.001	0.003	0.011
Total		76.17	76.01	78.91	76.07	78.98	80.28	1.61	0.071	0.001	0.494
Total amino acids		77.31	77.45	79.66	77.86	80.41	81.87	1.37	0.013	0.001	0.126

[1]Each least squares mean represents 7 observations.

[2]Linear effects of particle size of corn.

Table 4. Effects of diet form and particle size of corn on standardized ileal digestibility (SID) of crude protein and amino acids in diets fed to growing pigs[1,2]

Item, % Diet form	Meal			Pellet				Contrast *P*-value		
Corn particle size, μm	700	500	300	700	500	300	SEM	Diet form	Particle size[3]	Interaction
Crude protein	80.30	82.19	81.49	81.65	84.47	86.08	1.87	0.018	0.043	0.033
Indispensable amino acids										
Arg	91.73	91.96	92.08	91.95	93.96	94.59	1.01	0.008	0.034	0.052
His	84.10	84.87	85.90	84.96	87.13	87.78	1.14	0.024	0.012	0.118
Ile	81.81	82.42	83.63	82.50	85.03	86.94	1.41	0.021	0.009	0.080
Leu	83.64	84.92	85.77	85.31	87.30	88.86	1.14	0.002	0.003	0.010
Lys	86.20	86.05	87.59	87.75	88.77	90.36	1.11	0.002	0.023	0.015
Met	86.25	86.61	89.84	89.26	90.77	92.55	0.96	< 0.001	< 0.001	0.001
Phe	82.85	83.50	84.37	83.87	86.45	87.75	1.22	0.004	0.009	0.029
Thr	78.78	79.81	81.17	81.01	83.25	84.26	1.49	0.007	0.028	0.037
Trp	84.36	84.03	84.55	86.30	86.95	86.14	1.38	0.030	0.988	0.134
Val	79.65	80.35	80.97	81.42	83.82	85.93	1.53	0.003	0.028	0.013
Total	84.13	84.74	85.82	85.49	87.51	88.87	1.18	0.003	0.009	0.020
Dispensable amino acids										
Ala	81.24	82.75	84.54	84.80	86.00	88.55	1.39	< 0.001	0.002	0.001
Asp	81.55	81.86	83.77	82.25	84.86	85.71	1.32	0.025	0.007	0.183
Cys	73.49	75.31	80.04	77.64	81.50	80.94	1.55	< 0.001	< 0.001	0.029
Glu	85.73	85.94	87.11	86.71	88.93	88.89	1.09	0.002	0.015	0.052
Gly	82.15	80.54	84.13	80.22	84.02	85.37	2.77	0.606	0.115	0.876
Pro	125.87	124.33	126.23	117.85	120.59	124.24	5.22	0.057	0.241	0.087
Ser	83.61	84.60	85.53	85.46	87.81	88.90	1.23	0.001	0.006	0.007
Tyr	83.86	84.77	86.18	86.15	88.14	88.83	1.07	0.001	0.007	0.008
Total	88.32	88.71	90.26	88.70	90.93	91.99	1.61	0.066	0.009	0.260
Total amino acids	86.05	86.60	87.91	86.93	89.04	90.27	1.37	0.014	0.006	0.074

[1]Each least squares mean represents 7 observations.

[2]Values for SID were calculated by correcting apparent ileal digestibility for basal ileal endogenous losses. Basal ileal endogenous losses were determined (g/kg dry matter intake) as: crude protein, 16.67; Arg, 0.65; His, 0.18; Ile, 0.33; Leu, 0.52; Lys, 0.41; Met, 0.08; Phe, 0.30; Thr, 0.53; Trp, 0.09; Val, 0.49; Ala, 0.60; Asp, 0.80; Cys, 0.19; Glu, 0.93; Gly, 1.57; Pro, 5.74; Ser, 0.48; Tyr, 0.27; and total amino acids, 14.43.

[3]Linear effects of particle size of corn.

Table 5. Effects of diet form and particle size of corn on apparent total tract digestibility (ATTD) of dry matter (DM) and gross energy (GE) and concentrations of digestible energy (DE), metabolizable energy (ME), and net energy (NE) in diets and total heat production (THP) and fasting heat production (FHP) from group-housed pigs[1]

Item / Diet form	Meal			Pellet				Contrast *P*-value		
Corn particle size, µm	700	500	300	700	500	300	SEM	Diet form	Particle size[2]	Interaction
Intake										
Feed intake, kg/d	2.72	2.62	2.73	2.66	2.61	2.60	0.18	0.254	0.684	0.197
Orts, kg/d	0.08	0.08	0.09	0.04	0.03	0.04	0.01	< 0.001	0.328	< 0.001
GE intake, Mcal/d	10.66	10.15	10.69	10.53	10.36	10.28	0.72	0.628	0.693	0.340
Fecal excretion										
Dry feces output, kg/d	0.27	0.23	0.23	0.23	0.20	0.22	0.02	0.001	0.010	0.002
GE in feces, kcal/kg	4,539	4,568	4,147	4,087	3,988	3,905	61	< 0.001	< 0.001	< 0.001
Feces GE output, kcal/d	1,244	1,032	962	924	807	840	60	< 0.001	< 0.001	< 0.001
ATTD of DM, %	89.87	91.25	91.39	91.38	92.23	91.69	0.38	0.004	0.019	0.019
ATTD of GE, %	88.26	89.70	90.89	91.08	92.22	91.79	0.45	< 0.001	< 0.001	< 0.001
Urine excretion										
Urine output, kg/d	6.11	5.90	6.81	4.87	5.22	5.68	0.56	0.001	0.034	0.002
GE in urine, kcal/kg	33.23	33.01	29.19	34.91	35.23	35.05	2.27	0.049	0.318	0.061
Urine GE output, kcal/d	206	197	194	170	183	194	22	0.075	0.583	0.108
Heat increment										
ME intake, kcal/BW$^{0.6}$/d	755	725	778	757	763	749	43	0.814	0.727	0.537
THP, kcal/d	4,314	4,216	4,218	4,346	4,315	4,299	254	0.166	0.250	0.361
THP, kcal/BW$^{0.6}$/d	358	342	345	350	356	355	23	0.182	0.440	0.759
FHP, kcal/ BW$^{0.6}$/d	212	201	203	207	218	221	16	0.019	0.588	0.196
Retained energy, kcal/d	4,892	4,710	5,313	5,090	5,053	4,946	477	0.782	0.593	0.744
Respiratory quotient, fed[3]	0.65	0.69	0.67	0.69	0.67	0.71	0.04	0.129	0.293	0.022
Respiratory quotient, fasted	1.01	1.03	1.00	1.02	1.03	1.03	0.05	0.469	0.868	0.306
Energy in diets, kcal/kg										
DE	3,459	3,477	3,560	3,599	3,667	3,633	18	< 0.001	< 0.001	< 0.001
ME	3,385	3,402	3,488	3,535	3,596	3,559	18	< 0.001	< 0.001	< 0.001
NE	2,735	2,739	2,838	2,857	2,957	2,926	60	< 0.001	0.015	0.004
Energy efficiency, %										
ME to DE	97.85	97.87	97.98	98.23	98.06	97.98	0.15	0.045	0.601	0.098
NE to ME	80.79	80.50	81.35	80.81	82.24	82.19	1.57	0.165	0.200	0.564

[1]Each least squares mean represents 6 observations.
[2]Linear effects of particle size of corn.
[3]Even though the interaction was significant, mean separation using Tukey's adjustment was not significant.

Table 6. Effects of diet form and particle size of corn on apparent total tract digestibility (ATTD) of total dietary fiber (TDF), soluble dietary fiber (SDF), acid hydrolyzed ether extract (AEE), Ca, and P and N balance in diets fed to group-housed pigs[1]

Item	Diet form	Meal			Pellet				Contrast *P*-value		
	Corn particle size, µm	700	500	300	700	500	300	SEM	Diet form	Particle size[2]	Interaction
Ca digestibility											
Ca intake, g/d		15	15	15	15	15	14	1.02	0.254	0.684	0.197
Ca in feces, %		1.78	1.79	2.41	2.65	2.88	3.11	0.21	< 0.001	0.001	< 0.001
Ca excretion in feces, g/d		4.91	4.01	5.67	6.13	5.95	6.77	0.71	0.001	0.119	0.014
Absorbed Ca, g/d		10.25	10.60	9.55	8.72	8.58	7.72	0.75	0.001	0.133	0.006
ATTD of Ca, %		67.79	72.58	62.35	58.86	59.84	54.18	3.31	< 0.001	0.066	0.004
P digestibility											
P intake, g/d		13	12	13	12	12	12	0.85	0.254	0.684	0.197
P in feces, %		2.20	2.29	2.57	2.77	3.01	2.79	0.12	< 0.001	0.042	< 0.001
P excretion in feces, g/d		6.07	5.12	6.01	6.33	6.16	6.08	0.55	0.076	0.619	0.584
Absorbed P, g/d		6.58	7.06	6.68	6.07	5.95	6.00	0.55	0.032	0.965	0.158
ATTD of P, %		52.19	57.61	52.14	48.61	49.87	50.25	2.65	0.037	0.747	0.271
N balance											
N intake, g/d		56	52	55	54	53	54	3.73	0.618	0.931	0.313
N in feces, %		3.40	3.51	3.39	3.32	3.28	3.21	0.13	0.093	0.606	0.267
N excretion in feces, g/d		9.29	7.91	7.93	7.49	6.63	6.89	0.55	0.001	0.043	0.005
Absorbed N, g/d		46.38	44.32	47.24	46.09	46.77	47.44	3.45	0.516	0.459	0.977
ATTD of N, %		83.19	84.56	85.49	85.63	87.56	87.25	0.97	0.002	0.031	0.021
N in urine, %		0.19	0.24	0.16	0.24	0.22	0.21	0.05	0.163	0.203	0.029
N excretion in urine, g/d		12.53	15.97	11.55	12.00	12.15	13.21	3.54	0.526	0.944	0.743
N retention, g/d		33.85	28.35	35.68	34.09	34.63	34.22	2.50	0.414	0.697	0.809
N retention, % intake		61.81	56.42	65.50	64.79	65.86	64.47	5.48	0.181	0.620	0.775
N retention, % absorbed		74.48	66.80	76.55	75.92	75.30	73.98	6.72	0.421	0.985	0.879
TDF digestibility											
TDF intake, g/d		296	238	276	280	253	273	18.62	0.771	0.065	0.188
TDF in feces, %		40.07	39.30	42.75	45.17	42.10	45.65	1.72	0.007	0.306	0.014
TDF excretion in feces, g/d		110	91	100	102	86	99	9.20	0.398	0.314	0.503
Absorbed TDF, g/d		186	148	175	177	167	174	14.28	0.706	0.479	0.601
ATTD of TDF, %		62.71	61.85	63.48	63.07	66.30	63.75	2.52	0.395	0.765	0.896
SDF digestibility											
SDF intake, g/d		8	16	11	19	13	26	1.16	< 0.001	< 0.001	< 0.001
SDF in feces, %		2.44	3.72	3.68	3.95	3.48	3.42	0.45	0.218	0.291	0.070
SDF excretion in feces, g/d		6.66	8.62	8.55	9.25	7.43	7.34	1.31	0.910	0.989	0.327
Absorbed SDF, g/d		1.49	7.10	2.37	9.40	5.60	18.63	0.97	< 0.001	< 0.001	< 0.001
ATTD of SDF, %		17.34	46.52	21.35	52.29	45.23	72.09	6.23	< 0.001	0.015	< 0.001

IDF digestibility										
IDF intake, g/d	288	223	265	261	240	247	17.53	0.108	0.011	0.004
IDF in feces[3], %	37.33	35.58	38.13	41.22	38.62	42.23	1.66	0.008	0.565	0.017
IDF excretion in feces, g/d	103	82	89	93	78	91	8.13	0.484	0.229	0.578
Absorbed IDF, g/d	186	141	176	168	161	155	13.98	0.451	0.230	0.048
ATTD of IDF, %	64.29	62.93	66.14	63.84	67.44	62.88	2.53	0.896	0.860	0.459
AEE digestibility										
AEE intake, g/d	122	116	125	135	134	133	8.89	< 0.001	0.940	0.006
AEE in feces, %	14.53	16.13	12.09	9.86	10.92	9.20	0.63	< 0.001	0.019	< 0.001
AEE excretion in feces, g/d	40	36	28	22	22	20	2.43	< 0.001	0.002	< 0.001
Absorbed AEE, g/d	82	80	97	113	112	113	7.49	< 0.001	0.053	< 0.001
ATTD of AEE, %	67.12	68.53	77.13	83.33	83.60	84.97	1.45	< 0.001	< 0.001	< 0.001

[1]Each least squares mean represents 6 observations.
[2]Linear effects of particle size of corn.
[3]Even though the interaction was significant, mean separation using Tukey's adjustment was not significant.

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