



Interactive effects of pelleting and particle size reduction of corn on ileal digestibility of starch, acid-hydrolyzed ether extract, and amino acids in corn-soybean meal diets fed to growing pigs

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ABSTRACT

The objective was to test the hypothesis that pelleting and reducing corn particle size separately or in combination increase the apparent ileal digestibility (AID) of starch and acid-hydrolyzed ether extract (AEE) and standardized ileal digestibility (SID) of amino acids (AA) in diets fed to growing pigs. Six corn-soybean meal-based diets were formulated using three particle sizes of corn (i.e., 700, 500, or 300 μ m) and two diet forms (i.e., meal or pelleted). A nitrogen-free diet was also used. Seven pigs (initial weight: 59.3 kg) that had a T-cannula installed in the distal ileum were allotted to the seven diets using a 7×7 Latin square design with 7 periods. Ileal digesta were collected for 2 days of each period. Results indicated that there were no interactions between particle size and diet form for the SID of AA. However, the AID of AEE was increased by reducing the particle size of corn, but the increase was greater in meal diets than in pelleted diets (interaction; $P < 0.001$). The AID of starch also was increased by reducing the particle size of corn in meal diets, but not in pelleted diets (tendency for an interaction; $P = 0.060$). Regardless of particle size, the ileal digestibility of AEE, starch, and most AA was greater ($P < 0.05$) in pelleted diets than in meal diets. Regardless of diet form, the ileal digestibility of AEE, starch, and most AA increased (linear; $P < 0.05$) by reducing the particle size of corn. In conclusion, reducing corn particle size affects starch and AEE digestibility differently in meal and pelleted diets, but both pelleting and reducing particle size increase the AA digestibility.

1. Introduction

Reducing the particle size of cereal grains increases the digestibility of starch and energy by pigs (Huang et al., 2015; Rojas and Stein, 2015; Lee et al., 2024) and it is likely that surface area of grain particles and interactions between particles and digestive enzymes are increased by reducing particle sizes. In contrast to the demonstrated improvement in the digestibility of starch and energy, effects of particle size reduction on digestibility of amino acids (AA) in different feed ingredients have been inconsistent (Fastinger and Mahan, 2003; Huang et al., 2015; Rojas and Stein, 2015; Ibagón et al., 2024a).

Pelleting may increase the digestibility of AA because the hydrogen bonds in proteins are broken by heat, which results in protein

Abbreviations: AA, amino acids; AEE, acid-hydrolyzed ether extract; AID, apparent ileal digestibility; ATTD, apparent total tract digestibility; CP, crude protein; DM, dry matter; SID, standardized ileal digestibility.

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denaturation and thus in increased AA digestibility by pigs. Applying heat, moisture, and pressure during the pelleting process also results in inactivation of some antinutritional factors including protease inhibitors, polyphenols, or lectins (Samtiya et al., 2020), which may increase AA digestibility (Lahaye et al., 2008; Svihus and Zimonja, 2011; Rojas et al., 2016). However, pelleting also reduces the particle size of grain (“secondary grinding”; Vukmirović et al. 2017), but it is not known if improvements in starch and AA digestibility obtained by reducing the particle size of grain and structural changes and “secondary grinding” obtained by pelleting are additive or if there are interactions between particle size reduction and pelleting. Pelleting also improves apparent total tract digestibility (ATTD) of acid-hydrolyzed ether extract (AEE; Lee et al., 2024), but it is not known if pelleting or particle size reduction influences the ileal digestibility of AEE. Corn is the primary source of energy and starch in swine diets. Therefore, applying feed technologies such as pelleting and particle size reduction to corn may bring nutritional benefits. Therefore, the objective of this experiment was to test the hypothesis that particle size reduction and pelleting, separately or in combination, increase the apparent ileal digestibility (AID) of AEE, starch, and AA and the standardized ileal digestibility (SID) of AA in corn-soybean meal diets fed to growing pigs.

2. Material and methods

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocol for this experiment (protocol #: 21247). Pigs were the offspring of Line 900 boars and Camborough females (Pig Improvement Company, Hendersonville, TN, USA).

2.1. Diets and diet preparation

One batch of yellow dent corn was ground to 3 particle sizes (i.e., 700, 500, or 300 μm) using a 3-high roller mill (Model 924; RMS, Harrisburg, SD, USA) before being included in experimental diets based on corn and soybean meal. Dietary treatments were prepared using a 3×2 factorial treatment arrangement with the three particle sizes of corn and two diet forms (i.e., meal or pelleted; Tables 1 and 2). All diets were formulated to contain all nutrients at or above the requirements for 30–115 kg pigs (NRC, 2012). Diets were produced at the Kansas State University O.H. Kruse Feed Technology and Innovation Center (Manhattan, KS, USA). Details on diet preparation (i.e., grinding and pelleting), particle size measurements, and analyzed nutrient composition of diets have been reported (Lee et al., 2024). Analyzed particle sizes of the three sources of corn were 685, 526, and 320 μm , respectively (Lee et al., 2024). Briefly, diets were steam-conditioned at 83 °C for 30 s, subsequently pelleted at a speed of 15.2 kg/min, and had a hot pellet temperature of 88.5 °C. No pelleting aids were used. In addition to the six corn-soybean meal diets, a nitrogen-free diet was also used to

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

Item, g/kg Diet form:	Meal			Pellet ^b			Nitrogen-free ^c
Corn particle size ^a , μm :	700	500	300	700	500	300	
Ground corn, 700 μm	781.00	-	-	781.00	-	-	-
Ground corn, 500 μm	-	781.00	-	-	781.00	-	-
Ground corn, 300 μm	-	-	781.00	-	-	781.00	-
Soybean meal, 48 % crude protein	171.50	171.50	171.50	171.50	171.50	171.50	-
Corn starch	-	-	-	-	-	-	675.0
Sucrose	-	-	-	-	-	-	200.0
Soybean oil	15.00	15.00	15.00	15.00	15.00	15.00	40.0
Cellulose	-	-	-	-	-	-	40.0
Monocalcium phosphate	-	-	-	-	-	-	16.5
Dicalcium phosphate	8.91	8.91	8.91	8.91	8.91	8.91	-
Ground limestone	7.00	7.00	7.00	7.00	7.00	7.00	10.5
L-Lys-HCl, 78.8 % Lys	2.72	2.72	2.72	2.72	2.72	2.72	-
D,L-Met, 99 % Met	0.24	0.24	0.24	0.24	0.24	0.24	-
L-Thr, 99 % Thr	0.63	0.63	0.63	0.63	0.63	0.63	-
Sodium chloride	4.00	4.00	4.00	4.00	4.00	4.00	4.0
Titanium dioxide	4.00	4.00	4.00	4.00	4.00	4.00	4.0
Vitamin-mineral premix ^d	5.00	5.00	5.00	5.00	5.00	5.00	5.0
Potassium carbonate	-	-	-	-	-	-	4.0
Magnesium oxide	-	-	-	-	-	-	1.0

^a Analyzed particle sizes of the three sources of corn were 685, 526, and 320 μm , respectively (adapted from Lee et al., 2024).

^b No pelleting aids were used when diets were prepared.

^c Analyzed dry matter and ash in the nitrogen-free diet were 922.1 and 38.0 g/kg, respectively.

^d The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kg of complete diet: vitamin A as retinyl acetate, 10,622 IU; vitamin D₃ as cholecalciferol, 1660 IU; vitamin E as D,L- α -tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.40 mg; thiamin as thiamine mononitrate, 1.08 mg; riboflavin, 6.49 mg; pyridoxine as pyridoxine hydrochloride, 0.98 mg; vitamin B₁₂, 0.03 mg; D₅-pantothenic acid as D₅-calcium pantothenate, 23.2 mg; niacin, 43.4 mg; folic acid, 1.56 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 123 mg as iron sulfate; I, 1.24 mg as ethylenediamine dihydroiodide; Mn, 59.4 mg as manganese hydroxychloride; Se, 0.27 mg as sodium selenite and selenium yeast; and Zn, 124.7 mg as zinc hydroxychloride.

Table 2

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

Item, g/kg Diet form:	Meal			Pellet		
Corn particle size, μm :	700	500	300	700	500	300
Dry matter	895	895	894	901	906	899
Acid-hydrolyzed ether extract	45.7	44.3	44.8	51.0	51.6	50.7
Starch	480	504	486	494	487	480
Crude protein (nitrogen $\times$ 6.25)	135	131	129	123	128	132
Lys to crude protein	72.1	66.6	79.1	75.6	77.5	76.5
Indispensable amino acids						
Arg	9.1	8.6	9.8	8.7	9.4	9.5
His	3.9	3.8	4.2	3.8	4.1	4.2
Ile	6.3	6.0	6.8	5.9	6.3	6.5
Leu	13.7	13.5	14.5	13.6	14.2	14.5
Lys	9.7	8.7	10.2	9.3	9.9	10.1
Met	2.6	2.4	3.1	2.5	2.8	2.9
Phe	7.4	7.1	7.9	7.2	7.6	7.7
Thr	6.0	5.6	6.2	5.8	6.2	6.2
Trp	1.3	1.2	1.2	1.3	1.4	1.3
Val	7.2	6.8	7.2	6.8	7.2	7.5
Total	67.2	63.7	71.1	64.9	69.1	70.4
Dispensable amino acids						
Ala	8.1	7.9	8.5	8.0	8.4	8.5
Asp	14.3	13.2	15.4	13.3	14.5	14.7
Cys	2.5	2.5	2.9	2.5	2.8	2.8
Glu	26.3	25.2	28.1	25.3	26.8	27.3
Gly	6.1	5.7	6.5	5.8	6.2	6.3
Pro	9.3	9.3	10.0	9.5	9.7	9.8
Ser	6.3	5.9	6.6	6.1	6.5	6.6
Tyr	5.1	4.9	5.4	5.0	5.3	5.3
Total	78.0	74.6	83.4	75.5	80.2	81.3

determine basal endogenous losses of crude protein (CP) and AA, and there were, therefore, a total of seven diets in the experiment. The nitrogen-free diet was modified after [Stein et al. \(2007\)](#). All diets contained TiO_2 as an indigestible marker.

2.2. Animals, housing, and sample collection

Seven growing pigs (initial body weight = 59.3 ± 2.8 kg) that were equipped with a T-cannula in the distal ileum were allotted to dietary treatments using a 7×7 Latin square design with seven pigs, seven treatments, and seven periods ([Kim and Stein, 2009](#)). Therefore, there were seven replicate pigs per treatment. Cannulas were installed ([Stein et al., 1998](#)) when pigs had a body weight of approximately 21 kg, and they had been used in a previous experiment before being fed a common grower diets for 13 days and then allotted to diets in this experiment. Pigs were placed in pens that had a feeder, a drinking nipple, and fully slatted tribar floors. Water and feed were available at all times.

Each experimental period lasted seven days. The initial five days of each period were considered the adaptation period to the diet, but ileal digesta were collected on days 6 and 7 for nine hours per day ([Stein et al., 1998](#)). In short, the cannulas were opened and a plastic bag (7.6×20.3 cm; Uline, Pleasant Prairie, WI, USA) 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 bag, and all samples were stored at -20°C as soon as collected ([Lee et al., 2021](#)). At the conclusion of the 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 before chemical analysis ([Lagos and Stein, 2019](#)).

2.3. Chemical analysis

All diets and ileal digesta samples were ground using a coffee grinder before being analyzed. Diet and ileal digesta samples were analyzed for dry matter (DM; method 930.15; [AOAC Int, 2019](#)). Nitrogen in diets and ileal digesta samples was determined using a LECO FP628 Nitrogen Analyzer (LECO Corp., Saint Joseph, MI, USA; [AOAC Int, 2019](#); method 990.03) and CP was calculated as analyzed nitrogen $\times$ 6.25. Amino acids in diets and ileal digesta samples were analyzed on a Hitachi Amino Acid Analyzer, Model No. L8800 (Hitachi High Technologies America, Inc; Pleasanton, CA, USA) using method 982.30 E, a, b, c ([AOAC Int, 2019](#)). Diet and ileal digesta samples from pigs fed the six corn-soybean meal diets (but not digesta from pigs fed the nitrogen-free diet) were analyzed for starch using the glucoamylase procedure (method 979.10; [AOAC Int, 2019](#)). These sample were also analyzed for AEE by acid-hydrolysis using 3 N HCl (AnkomHCl; Ankom Technology, Macedon, NY, USA) followed by crude fat extraction using petroleum ether (method 2003.06; [AOAC Int, 2019](#)) on an Ankom fat analyzer (AnkomXT15; Ankom Technology, Macedon, NY, USA). Titanium in diets and ileal digesta samples was determined following the procedure of [Myers et al. \(2004\)](#).

2.4. Calculations

The basal endogenous losses of CP and AA were calculated using the analyzed DM, CP (nitrogen $\times$ 6.25), AA, and Ti in ileal digesta samples from pigs fed the nitrogen-free diet and the analyzed DM and Ti in the nitrogen-free diet as previously described (Stein et al., 2007). Apparent ileal digestibility was calculated using the analyzed CP, AA, AEE, starch, and Ti concentrations in diets and ileal digesta, and the SID of CP and AA was calculated by correcting the AID values for basal endogenous losses of CP and AA, respectively (Stein et al., 2007).

2.5. Statistical analysis

Homogeneity of the variances and normality were confirmed using a residual plot and the Shapiro-Wilk test, respectively, and data were analyzed using the PROC MIXED in SAS. If values deviated from the 1st or 3rd quartiles by more than 3 times the interquartile range, the values were considered as outliers (Tukey, 1977), but no outliers were identified. The statistical model included diet as the fixed variable and pig and period as the random variables. Contrast statements were used to test effects of diet form, linear effects of particle size, and the interaction between diet form and linear effects of particle size. Mean values were calculated using the LSMeans statement. Pig was the experimental unit. Results were considered significant at $P < 0.05$ and considered a trend at $P < 0.10$.

3. Results

Pigs remained healthy during the experiment and pigs consumed their assigned diets without any apparent problems. All pigs that were assigned to treatments completed the experiment.

3.1. AID of DM, AEE, starch, and AA

Results indicated that there were no interactions between particle size of corn and pelleting for the AID of DM and the AID of most AA except for Arg (Table 3). The AID of AEE was increased by pelleting or reduced corn particle size, but the increase was greater if diets were in a meal form than in a pelleted form (interaction; $P < 0.001$). The AID of starch was increased by reducing corn particle size if diets were in a meal form, but that was not the case if diets were pelleted (tendency for an interaction; $P = 0.060$). The AID of CP and Arg was increased by reducing particle size, but more so in pelleted diets than in meal diets (tendency for an interaction; $P < 0.10$).

The AID of DM was not affected by diet form or particle size of corn. Regardless of particle size, the AID of AEE, starch, CP, and all

Table 3

Effects of diet form and particle size of corn on apparent ileal digestibility of dry matter, acid-hydrolyzed ether extract, starch, crude protein, and amino acids in diets fed to growing pigs^a.

Item, g/kg Diet form:	Meal			Pellet			SEM	Contrast P-value		
	700	500	300	700	500	300		Diet form	Particle size ^b	Interaction
Corn particle size, μm :										
Dry matter	0.721	0.740	0.737	0.735	0.754	0.753	0.013	0.131	0.152	0.957
Acid-hydrolyzed ether extract	0.638	0.686	0.743	0.792	0.852	0.835	0.029	< 0.001	0.007	< 0.001
Starch	0.946	0.950	0.979	0.969	0.960	0.979	0.007	0.029	0.001	0.060
Crude protein (nitrogen $\times$ 6.25)	0.692	0.708	0.699	0.694	0.727	0.747	0.019	0.042	0.032	0.095
Indispensable amino acids										
Arg	0.853	0.852	0.861	0.852	0.877	0.884	0.010	0.009	0.006	0.083
His	0.800	0.807	0.821	0.808	0.832	0.840	0.011	0.021	0.004	0.514
Ile	0.772	0.775	0.793	0.775	0.803	0.824	0.014	0.029	0.004	0.221
Leu	0.802	0.815	0.826	0.818	0.840	0.856	0.011	0.002	0.001	0.396
Lys	0.825	0.819	0.840	0.838	0.851	0.868	0.011	0.001	0.012	0.420
Met	0.834	0.835	0.875	0.863	0.881	0.900	0.010	< 0.001	< 0.001	0.806
Phe	0.792	0.797	0.810	0.801	0.829	0.842	0.012	0.004	0.005	0.219
Thr	0.709	0.714	0.736	0.728	0.755	0.766	0.015	0.005	0.013	0.639
Trp	0.779	0.771	0.776	0.798	0.809	0.797	0.014	0.010	0.834	0.932
Val	0.736	0.739	0.749	0.750	0.777	0.801	0.015	0.003	0.016	0.140
Total	0.794	0.797	0.813	0.805	0.828	0.843	0.012	0.003	0.004	0.315
Dispensable amino acids										
Ala	0.747	0.760	0.783	0.781	0.796	0.822	0.014	< 0.001	0.001	0.787
Asp	0.766	0.765	0.791	0.769	0.799	0.808	0.013	0.031	0.002	0.475
Cys	0.667	0.686	0.742	0.708	0.754	0.749	0.016	< 0.001	< 0.001	0.128
Glu	0.826	0.826	0.842	0.834	0.858	0.858	0.011	0.002	0.007	0.544
Gly	0.590	0.558	0.625	0.558	0.610	0.629	0.028	0.663	0.023	0.402
Pro	0.706	0.690	0.749	0.634	0.670	0.715	0.052	0.079	0.037	0.493
Ser	0.768	0.773	0.791	0.784	0.812	0.824	0.012	0.001	0.002	0.331
Tyr	0.790	0.798	0.816	0.812	0.834	0.842	0.011	0.001	0.003	0.826
Total	0.762	0.760	0.789	0.761	0.790	0.803	0.016	0.071	0.001	0.429

^a Each least squares mean represents 7 observations.

^b Linear effects of particle size of corn.

AA except Gly and Pro was greater ($P < 0.05$) in pelleted diets than in meal diets, but the AID of Pro tended to be greater ($P = 0.079$) in meal diets than in pelleted diets. Regardless of diet form, the AID of AEE, starch, CP, and all AA except Trp increased (linear; $P < 0.05$) when corn particle size was reduced.

3.2. SID of AA

There were no interactions between particle size of corn and pelleting for the SID of CP and AA with the exception that there was a tendency ($P = 0.099$) for an interaction between diet form and particle size for the SID of Arg because reducing corn particle size increased the SID of Arg only in pelleted diets (Table 4). Regardless of particle size, the SID of all AA except Gly and Pro was greater ($P < 0.05$) in pelleted diets than in meal diets. However, the SID of Pro tended ($P = 0.059$) to be greater in meal diets than in pelleted diets. Regardless of diet form, values for the SID of all AA except Trp, Gly, and Pro increased (linear; $P < 0.05$) if particle size of corn was reduced from 700 to 300 μm .

4. Discussion

Analyzed concentrations of CP and AA in diets were slightly less than calculated values, but the SID of AA in the meal diet containing corn ground to 700 μm was in agreement with calculated values (NRC, 2012). The basal endogenous losses of AA were within the range of values previously summarized (Lee and Stein, 2023) and predicted values (Park et al., 2024). Regardless of particle size, the analyzed concentrations of AEE in the meal diets were within the range of expected values (NRC, 2012), but the analyzed AEE was greater in the pelleted diets than in the meal diets, which indicated that pelleting increases AEE in diets. Although moisture loss during pelleting may concentrate AEE on an as-is basis, the concentration of AEE in pelleted diets was more than 10 % greater than in meal diets on a DM basis. We are not aware of previous data on the effects of pelleting on the concentration of AEE in feed ingredients or diets, but it is possible that the heat and pressure that are generated during pelleting release some of the fat that is encapsulated in the fiber matrix of corn or soybean meal, which results in greater analyzed values for AEE. It is, however, also possible that analyzed AEE in pelleted diets is influenced by analytical inaccuracies that overestimate AEE, but we do not have data to support this hypothesis.

The AID of AEE and starch in the meal diet containing 700 μm corn, soybean meal, and soybean oil was within the range of expected values (Kim et al., 2013; Rundle et al., 2023; Lee et al., unpublished data). The observation that the increases in the AID of AEE and starch when the particle size of corn was reduced from 700 to 300 μm were greater in meal diets than in pelleted diets agreed with data for ATTD of AEE, energy, and thus net energy in diets (Lee et al., 2024). These data also are in agreement with results demonstrating that reduction of the particle size of field peas increased net energy, which was also attributed to an increased AID of starch (Ibagon et al., 2024a, 2024b). The reason why effects of particle size reduction on AID of AEE and starch is greater in meal diets than in pelleted

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^{a,b}.

Item, % Diet form:	Meal			Pellet			SEM	Contrast P-value		
	700	500	300	700	500	300		Diet form	Particle size ^c	Interaction
Corn particle size, μm :										
Crude protein (nitrogen $\times$ 6.25)	0.803	0.822	0.815	0.817	0.845	0.861	0.019	0.018	0.043	0.230
Indispensable amino acids										
Arg	0.917	0.920	0.921	0.920	0.940	0.946	0.010	0.008	0.034	0.099
His	0.841	0.849	0.859	0.850	0.871	0.878	0.011	0.024	0.012	0.557
Ile	0.818	0.824	0.836	0.825	0.850	0.869	0.014	0.021	0.009	0.242
Leu	0.836	0.849	0.858	0.853	0.873	0.889	0.011	0.002	0.003	0.406
Lys	0.862	0.861	0.876	0.878	0.888	0.904	0.011	0.002	0.023	0.466
Met	0.863	0.866	0.898	0.893	0.908	0.926	0.010	< 0.001	< 0.001	0.830
Phe	0.829	0.835	0.844	0.839	0.865	0.878	0.012	0.004	0.009	0.223
Thr	0.788	0.798	0.812	0.810	0.833	0.843	0.015	0.007	0.028	0.724
Trp	0.844	0.840	0.846	0.863	0.870	0.861	0.014	0.030	0.988	0.880
Val	0.797	0.804	0.810	0.814	0.838	0.859	0.015	0.003	0.028	0.213
Total	0.841	0.847	0.858	0.855	0.875	0.889	0.012	0.003	0.009	0.351
Dispensable amino acids										
Ala	0.812	0.828	0.845	0.848	0.860	0.886	0.014	< 0.001	0.002	0.823
Asp	0.816	0.819	0.838	0.823	0.849	0.857	0.013	0.025	0.007	0.528
Cys	0.735	0.753	0.800	0.776	0.815	0.809	0.016	< 0.001	< 0.001	0.150
Glu	0.857	0.859	0.871	0.867	0.889	0.889	0.011	0.002	0.015	0.565
Gly	0.822	0.805	0.841	0.802	0.840	0.854	0.028	0.606	0.115	0.475
Pro	1.259	1.243	1.262	1.179	1.206	1.242	0.052	0.057	0.241	0.293
Ser	0.836	0.846	0.855	0.855	0.878	0.889	0.012	0.001	0.006	0.398
Tyr	0.839	0.848	0.862	0.862	0.881	0.888	0.011	0.001	0.007	0.835
Total	0.883	0.887	0.903	0.887	0.909	0.920	0.016	0.066	0.009	0.471

^a Each least squares mean represents 7 observations.

^b 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; and Tyr, 0.27.

^c Linear effects of particle size of corn.

diets is likely that friction is applied to feed particles during pelleting, which results in an additional reduction of feed particle size (Vukmirović et al. 2017). It is thus likely that the advantages of reducing the particle size of corn prior to mixing were reduced in pelleted diets compared with meal diets because pelleting reduced the particle size of the courser particles. However, there were no interactions between pelleting and particle size reduction for the SID of most AA, which indicates that the interactions in energy digestibility and net energy in diets observed in the previous experiment primarily were a result of changes in the AID of AEE and starch (Lee et al., 2024).

The observation that the ileal digestibility of starch, CP, and AA in diets were increased by pelleting agreed with data for field peas (Stein and Bohlke, 2007), wheat-based diets (Lahaye et al., 2008), or corn-soybean meal-based diets (Rojas et al., 2016; Chassé et al., 2022; Dunmire et al., 2024). The observation that the digestibility of fat was increased by pelleting also agreed with previous data (Noblet and Champion, 2003; Lee et al., 2024). Pelleting is a process where moisture, heat, and pressure are applied to diets and the increases in the AID of AEE and starch and the SID of CP and AA that are observed in pelleted diets are a result of the fact that moderate heating increases gelatinization of starch and denaturation of proteins, and some antinutritional factors including protease inhibitors, polyphenols, or lectins may be inactivated (Lancheros et al., 2020). Application of moderate heat and pressure during processing, therefore, has positive impacts on nutrient digestibility. However, over-heating of feed ingredients or diets during processing results in reduced concentration and digestibility of Lys and other AA (González-Vega et al., 2011), but the observation that the SID of CP and Lys and other AA was increased in pelleted diets compared with meal diets indicates that the heat applied during pelleting was not excessive. The observation that the AID of Pro in pelleted diets was less than in meal diets may be a result of differences in the Pro concentration of ileal digesta. Pigs fed pelleted diets secrete more mucin in the small intestine than pigs fed meal diets (Hedemann et al., 2005), and mucin is rich in Pro. Therefore, this contributes to greater endogenous losses of Pro, and thus, reduces the AID. However, the AID of Thr and Ser, which are the other major AA in mucin, was greater in pelleted diets compared with meal diets. This indicates that the increases in the AID of Thr and Ser by pelleting outweighed the increase in endogenous losses, resulting in a net increase in AID. The observation that there was no impact of treatment on SID of Gly is likely also related to changes in endogenous losses because Gly, like Pro, is also highly influenced by endogenous secretions into the small intestine. Indeed, more than 90 % of the bile acids are conjugated by Gly and deconjugated bile salts are largely resistant to enzymatic hydrolysis and reabsorption before the distal ileum (Stein et al., 1999).

The surface area is increased by reducing the particle size of feed ingredients, which allows digestive enzymes in the intestinal tract of pigs to have closer interaction with feed particles (Lyu et al., 2020), which results in increased digestibility of nutrients in diets. The observation that the AID of starch was increased by reducing particle size of corn agreed with previous data (Kim et al., 2009; Rojas and Stein, 2015; Lancheros et al., 2020). The AID of AEE was increased by reducing particle size of corn and this also agreed with previous experiment where the ATTD of ether extract was increased by reducing corn particle size (Lyu et al., 2020). A smaller particle size of corn also results in a more rapid digestion of starch than if greater particle sizes are used (Amaral et al., 2015), which may result in a more complete digestion of starch.

In the current experiment, ileal digestibility of CP and AA was increased by reducing particle size of corn, but this was not observed in some previous experiments (Fastinger and Mahan, 2003; Rojas and Stein, 2015; Ibagón et al., 2024a; Song et al., 2025). However, the AID of AA in lupins was increased by reducing the particle size (Kim et al., 2009) and it is not clear why responses to reduced particle size is inconsistent (Rojas and Stein, 2017). However, because particle size in the current experiment was reduced by using a 3-stacked roller mill (Lee et al., 2024), it is possible that friction heat was generated during grinding. It is, therefore, likely that more heat was generated during grinding in this experiment than in previous experiments where corn was ground using a hammer mill or a single roller mill, which may be the reason for the increased SID of AA observed in this experiment when particle size was reduced. Indeed, varying levels of heat treatment of soybean meal influenced the SID of AA with the greater SID observed when soybean meal was toasted at 115 °C (Messerschmidt et al., 2012). In addition, the ATTD of energy, DM, and nitrogen was increased if the particle size of corn was reduced using a roller mill whereas reducing the particle size of corn with a hammermill had no impact on digestibility of energy or nitrogen (Acosta et al., 2020). Thus, it appears that the type of grinding used to reduce the particle size of corn may impact the degree to which nutrient and energy digestibility is increased, which may be due to differences in the amount of heat generated during grinding. However, more research is needed to quantify possible differences in heat that contribute to these effects.

5. Conclusion

Effects of reducing particle size of corn on the AID of AEE and starch were greater in meal diets than in pelleted diets, but with a few exceptions, there were no interactions between pelleting and particle size reduction for AA digestibility. The AID of AEE and starch and the SID of almost all AA increased as particle size of corn was reduced. Likewise, the AID of AEE and starch and the SID of almost all AA were greater in pelleted diets than in meal diets, which is likely the reason both pelleting and reduction of particle size are effective in increasing the net energy of diets fed to growing pigs.

Author contributions

SAL and HHS conceptualized the experiments. CBP prepared experimental diets. SAL summarized data. HHS and SAL contributed with data interpretation. SAL wrote the first draft of the manuscript. HHS and CBP edited the final version of the manuscript. SAL and HHS supervised the project.

CRediT authorship contribution statement

Su A Lee: Writing – review & editing, Writing – original draft, Supervision, Investigation, Funding acquisition, Data curation, Conceptualization. **Chad B. Paulk:** Writing – review & editing, Resources. **Hans H. Stein:** Writing – review & editing, Supervision, Investigation, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Su A Lee reports financial support was provided by National Pork Board. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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