Published February 12, 2016

Effects of particle size of yellow dent corn on physical characteristics of diets and growth performance and carcass characteristics of growing–finishing pigs[1]

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ABSTRACT: The objectives of this experiment were to determine effects of reducing particle size on growth performance, carcass characteristics, stomach morphology, and VFA concentration in the hindgut of growing–finishing pigs if diets were formulated to a constant ME. Thirty-six gilts and 36 barrows (32.00 ± 1.58 kg initial BW) were individually penned and randomly allotted to 4 dietary treatments in a 2 × 4 factorial design with sex (gilts and barrows) and corn particle size (i.e., 865, 677, 485, and 339 µm) as factors. The ME was determined in the same 4 batches of corn in a previous experiment to be 3,826, 3,868, 3,895, and 3,964 kcal/kg DM, respectively. Pigs were fed a 3-phase program from 32 to 129 kg. Within each phase, 4 corn–soybean meal diets were formulated, and the only difference among diets was that the corn used was ground to the 4 specified particle sizes and soybean oil was added to the diets in decreasing amounts as the corn particle size was reduced to reflect the increased ME in corn with reduced particle size. Results of the experiment indicated that initial BW, final BW, overall ADFI, and overall ADG were not different among treatments, but final G:F for gilts decreased from 0.38 to 0.35 (linear, $P < 0.05$) as the particle size decreased from 865 to 339 µm, but no difference was observed for barrows (interaction, $P < 0.05$). However, G:F did not change if calculated based on HCW because dressing percentage increased (linear, $P < 0.01$) from 79.30 to 80.29% as the particle size decreased, which was partly due to a reduction (linear, $P < 0.01$) from 3.01 to 2.52 kg in empty intestinal weight. Back fat depth, HCW, loin eye area, and carcass fat-free lean percentage were not different among treatments. There were no incidences of ulcers in the esophageal region of the stomach regardless of the particle size of corn, but parakeratosis in the esophageal region increased ($P < 0.05$) as the particle size of corn decreased. The concentration of acetate, proprionate, and butyrate in the cecal contents decreased (linear, $P < 0.01$) from 2,537 to 1,846, from 872 to 617, and from 702 to 226 µg/mL, respectively, and the pH in the cecal and colon contents increased (linear, $P < 0.01$) from 6.04 to 6.64 and from 5.85 to 6.25, respectively, as the particle size decreased. In conclusion, by using corn ground to a smaller particle size, the amount of added fat may be reduced in the diets without affecting growth performance of barrows or carcass composition of barrows and gilts.

Key words: carcass characteristics, corn, fatty acids, growth performance, particle size, pigs

J. Anim. Sci. 2016.94:619–628
doi:10.2527/jas2015-9054

INTRODUCTION

Grinding of feed ingredients is used to reduce the particle size, which may increase surface area for enzyme action and thereby increase the digestibility of energy and nutrients (Kim et al., 2002; Fastinger and Mahan, 2003). A reduction in the particle size of corn from 865 to 677, 485, or 339 µm results in a linear increase in the ME of corn, and ME values of 3,826, 3,868, 3,895, and 3,964 kcal/kg DM were calculated for the 4 particle sizes (Rojas and Stein, 2015). These results are in agreement with data indicating that reducing

[1]Financial support for this research was provided by the National Pork Board (Des Moines, IA). Appreciation is also extended to Pioneer Hi-Bred (Johnston, IA) for donation of the corn grain used in this experiment and for grinding the grain to the specified particle sizes.

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Received February 28, 2015.
Accepted November 18, 2015.

the particle size of corn from 800 to 400 μm by using a hammer mill increased GE digestibility from 81.2 to 86.7% (Wondra et al., 1995b). The primary reason for the increased ME in corn ground to a smaller particle size was that the apparent ileal digestibility of starch was increased as the corn particle size was reduced (Rojas and Stein, 2015). In contrast, the digestibility and AA in corn was not influenced by the corn particle size (Rojas and Stein, 2015). Because of the increased ME of corn ground to a smaller particle size, less added fat is needed in diets containing corn ground to a smaller particle size compared with diets containing corn with a greater particle size, if diets are formulated to a constant ME. It is, therefore, hypothesized that addition of fat may be reduced without impacting pig growth performance if corn is ground to a smaller particle size. It is also hypothesized that the concentration of VFA in the hindgut of pigs is reduced if corn ground to a smaller particle size is included in the diet, because of reduced quantities of starch entering the hindgut. Therefore, the objectives of this experiment were to determine the effects of reducing the particle size on growth performance, carcass characteristics, stomach morphology, and VFA concentration in the hindgut of growing–finishing pigs fed diets formulated to a constant ME and to determine effects of corn particle size on physical characteristics of diets.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocol for this experiment.

Animals, Housing, Diets, and Experimental Design

Pigs used in the experiment were the offspring of G-performer boars mated to F-25 gilts (Genetiporc, Alexandria, MN). Corn (Pioneer P 0528) was grown in Iowa in 2011. The procedures used to obtain the desired mean particle sizes (i.e., 865, 677, 485, and 339 μm) of corn was previously described (Rojas and Stein, 2015; Table 1). Briefly, 1 lot of corn was divided into 4 batches that were ground to the specific particle sizes. Particle size distribution and mean particle size of the corn grains were determined using 100 g of grain that was placed on the top of the test sieves (U.S. sieve numbers 4, 6, 8, 12, 16, 20, 30, 40, 50, 70, 100, 140, 200, and 270, which correspond to openings of 4.76, 3.36, 2.38, 1.68, 1.19, 0.595, 0.42, 0.297, 0.21, 0.149, 0.105, 0.074, and 0.053 mm, and a solid metal pan), which were stacked from the biggest to the smallest aperture size. The test sieves were placed in a vibratory sieve shaker for 10 min. The feedstuff material in each of the test sieves was recorded and weighed for further calculations of mean particle size

Table 1. Chemical and physical composition of corn with different particle sizes and conventional soybean meal (SBM), as-fed basis

	Corn particle size, μm				
Item	865	677	485	339	SBM
GE, kcal/kg	3,920	3,900	3,914	3,870	4,197
DM, %	86.5	86.4	86.7	86.3	91.6
CP, %	7.08	7.23	7.25	7.00	47.7
Ash, %	1.15	1.39	1.23	1.10	5.67
AEE,[1] %	3.45	3.51	3.53	3.57	2.05
NDF, %	11.06	10.01	9.29	9.25	–
ADF, %	2.41	2.27	2.24	1.91	–
Starch, %	62.9	61.2	62.7	64.4	–
P, %	0.31	0.34	0.30	0.29	–
Ca, %	0.03	0.03	0.03	0.03	–
Indispensable AA, %					
Arg	0.35	0.37	0.35	0.35	3.39
His	0.20	0.21	0.20	0.20	1.22
Ile	0.24	0.26	0.25	0.24	2.20
Leu	0.85	0.84	0.83	0.83	3.78
Lys	0.25	0.26	0.25	0.25	3.02
Met	0.14	0.14	0.13	0.14	0.64
Phe	0.35	0.35	0.35	0.35	2.35
Thr	0.25	0.24	0.25	0.25	1.81
Trp	0.06	0.05	0.05	0.05	0.72
Val	0.35	0.38	0.36	0.35	2.45
Dispensable AA, %					
Ala	0.51	0.52	0.51	0.51	2.04
Asp	0.49	0.50	0.49	0.49	5.30
Cys	0.15	0.15	0.14	0.15	0.62
Glu	1.28	1.25	1.26	1.26	7.91
Gly	0.30	0.30	0.30	0.30	1.98
Pro	0.64	0.62	0.64	0.63	2.35
Ser	0.32	0.30	0.30	0.31	2.04
Tyr	0.20	0.22	0.20	0.21	1.67
Total AA	6.93	6.96	6.86	6.87	45.49
Physical composition					
Mean particle size, μm	865	677	485	339	785
SD of particle size	3.15	3.20	2.92	1.89	1.90
Surface area, cm^2/g	101	132	167	165	71.1
Filling angle of repose, °	46.8	50.7	54.9	57.4	73.2
Loose bulk density, g/L	651	632	601	565	706

[1]AEE = acid hydrolyzed ether extract.

(ANSI/ASAE, 2008). Soybean meal (**SBM**) that was locally sourced (Solae, Gibson City, IL) was also used.

A total of 36 gilts and 36 barrows with an average initial BW of 32.00 ± 1.58 kg were used. All pigs were individually housed in pens (0.9 by 1.8 m) with fully slatted concrete floors. A feeder and a nipple drinker were provided in each pen. Pigs were provided ad libitum access to feed and water throughout the experiment. Pigs were fed a 3-phase program (Table 2) with phase 1 diets being offered from approximately 32 to 62 kg (d 0 to 29), phase 2 diets from approximately 62 to 94 kg (d 29 to 58), and phase 3 diets from approximately 94 to 129

Table 2. Composition of experimental diets, as-fed basis[1]

	Corn particle size, µm											
	Phase 1				Phase 2				Phase 3			
Item	865	677	485	339	865	677	485	339	865	677	485	339
Ingredients, %												
Ground corn	66.07	67.17	67.14	67.76	71.47	72.61	72.52	73.22	76.33	77.57	77.45	78.22
Soybean meal, 48% CP	27.50	26.90	27.30	27.40	22.20	21.60	22.10	22.20	17.40	16.80	17.30	17.40
Soybean oil	3.60	3.12	2.78	2.00	3.74	3.23	2.85	2.00	3.87	3.30	2.92	2.00
Ground limestone	0.92	0.95	1.00	0.92	0.90	0.92	0.98	0.87	0.82	0.83	0.90	0.78
Dicalcium phosphate	0.90	0.87	0.77	0.92	0.71	0.68	0.57	0.74	0.60	0.55	0.45	0.64
L-Lysine HCL	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
DL-Methionine	0.10	0.10	0.11	0.10	0.07	0.07	0.08	0.07	0.06	0.05	0.07	0.05
L-Threonine	0.06	0.04	0.05	0.05	0.06	0.04	0.05	0.05	0.07	0.05	0.06	0.06
Sodium chloride	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin–mineral premix[2]	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Analyzed composition												
GE, kcal/kg	4,308	4,113	4,077	4,075	4,140	4,110	4,087	4,035	4,114	4,088	4,050	4,012
ME, kcal/kg[3]	3,396	3,396	3,396	3,396	3,412	3,412	3,412	3,412	3,412	3,412	3,412	3,412
DM, %	90.9	88.9	89.0	89.2	88.1	89.0	89.0	88.6	89.9	89.5	89.3	87.9
CP, %	18.6	18.3	18.4	18.6	15.1	15.0	15.4	15.5	14.2	14.0	14.1	14.1
Ash, %	4.74	3.71	4.15	4.04	3.29	3.42	3.82	4.02	3.25	3.34	3.26	3.24
AEE,[4] %	6.34	5.35	5.04	4.52	6.39	6.05	5.35	4.64	6.49	6.35	5.84	5.04
Indispensable AA, %												
Arg	1.25	1.14	1.20	1.22	1.01	0.94	1.02	1.01	0.87	0.85	0.86	0.96
His	0.48	0.45	0.47	0.48	0.41	0.38	0.42	0.41	0.36	0.36	0.36	0.39
Ile	0.80	0.73	0.77	0.80	0.66	0.60	0.68	0.65	0.57	0.57	0.56	0.62
Leu	1.56	1.51	1.57	1.63	1.38	1.29	1.43	1.39	1.27	1.30	1.24	1.37
Lys	1.32	1.03	1.20	1.11	0.94	0.87	0.95	0.92	0.80	0.73	0.82	0.86
Met	0.35	0.34	0.42	0.36	0.31	0.27	0.29	0.29	0.27	0.28	0.30	0.29
Phe	0.91	0.86	0.90	0.92	0.77	0.70	0.78	0.77	0.67	0.67	0.66	0.73
Thr	0.71	0.67	0.68	0.72	0.60	0.57	0.60	0.62	0.56	0.57	0.54	0.62
Trp	0.24	0.21	0.21	0.24	0.19	0.18	0.19	0.19	0.16	0.17	0.18	0.18
Val	0.93	0.86	0.93	0.95	0.82	0.71	0.80	0.77	0.68	0.71	0.72	0.73
Dispensable AA, %												
Ala	0.91	0.87	0.92	0.94	0.81	0.77	0.83	0.81	0.74	0.75	0.74	0.80
Asp	1.87	1.71	1.82	1.86	1.51	1.39	1.53	1.49	1.30	1.27	1.28	1.44
Cys	0.28	0.27	0.26	0.28	0.25	0.22	0.24	0.24	0.21	0.21	0.23	0.24
Glu	3.17	3.00	3.15	3.23	2.70	2.49	2.77	2.69	2.42	2.40	2.38	2.61
Gly	0.77	0.71	0.75	0.77	0.65	0.61	0.66	0.65	0.57	0.56	0.57	0.66
Pro	1.04	1.01	1.06	1.08	0.94	0.88	0.96	0.93	0.86	0.88	0.84	0.93
Ser	0.74	0.72	0.75	0.77	0.64	0.62	0.64	0.64	0.58	0.57	0.57	0.63
Tyr	0.60	0.58	0.60	0.62	0.52	0.46	0.52	0.51	0.44	0.44	0.45	0.50
Total AA	17.9	16.7	17.7	18.0	15.1	14.0	15.3	15.0	13.3	13.3	13.3	14.6

[1]All diets fed in phase 1 were formulated to contain 0.98% standardized ileal digestible (SID) Lys and 0.31% standardized total tract digestible (STTD) P. All diets fed in phase 2 were formulated to contain 0.85% SID Lys and 0.27% STTD P, and all diets fed in phase 3 were formulated to contain 0.73% SID Lys and 0.24% STTD P.

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

[3]Metabolizable energy values were calculated rather than analyzed (NRC, 2012; Rojas and Stein, 2015).

[4]AEE = acid hydrolyzed ether extract.

kg (d 58 to 93). Within each phase, 4 corn–SBM–based diets were formulated to meet or exceed current nutrient requirements (NRC, 2012). The amount of synthetic indispensable AA in each diet was adjusted based on the inclusion levels of corn and SBM. Diets within each phase were formulated using corn that was ground to 865, 677, 485, or 339 μm containing values for ME of 3,826, 3,868, 3,895, and 3,964 kcal/kg DM, respectively (Rojas and Stein, 2015). The corn used in the current experiment was from the same batches as the corn used by Rojas and Stein (2015). Diets within each phase were formulated to the same concentration of ME and standardized ileal digestible Lys, and addition of soybean oil was reduced to reflect the increase in ME that was assumed as the particle size of corn was reduced. Pigs were randomly allotted to the 4 dietary treatments in a 2 × 4 factorial design with sex (gilts and barrows) and corn particle size as factors. Nine gilts and 9 barrows were allotted to each diet. Two blocks of 36 pigs (18 gilts and 18 barrows) were used for a total of 72 pigs. The 2 blocks were allotted to treatment diets 7 d apart, and pigs in each block were harvested 1 wk apart to maintain the same number of days on feed for all pigs.

Feeding and Data Collection

All pigs were allowed ad libitum access to feed and water throughout the experiment. Individual pig BW was recorded at the start of the experiment, at the end of phase 1, at the end of phase 2, and at the conclusion of the experiment (d 93). Phases 1 and 2 each lasted 29 d and phase 3 lasted 35 d. Daily feed provisions were recorded as well, and feed left in the feeders was recorded on the same days as pig weights were recorded.

Slaughter, Sample Collection, and Carcass Evaluation

For each diet, 3 separate samples were collected for chemical and physical analysis. On d 93 of the experiment, feed was removed from the feeders and the final BW of pigs was recorded. After an overnight fast, pigs were transported to the Meat Science Laboratory at the University of Illinois (Urbana, IL) to be slaughtered. Pigs were handled, weighed, and slaughtered as described by Lee et al. (2013). The HCW, pH of the longissimus dorsi, back fat depth at the 10th rib, and the loin eye area (**LEA**) were also measured as described by Lee et al. (2013). The digestive tract was flushed with water to remove digesta, and the liver, heart, kidney, spleen, stomach, and intestines were patted dry and weighed. The score for the incidence of ulcers and parakeratosis in the pars esophageal section of the stomach was adapted from the system described by Nielsen and Ingvartsen (2000). In the current experiment, no major lesions were observed, and as a consequence, the scoring system was narrowed to a score between 0 and 3, where a score of 0 means no evidence of lesions, a score of 1 means minor parakeratosis, a score of 2 indicates medium parakeratosis, and a score of 3 indicates parakeratosis.

The pH of contents collected from the stomach, the ileum, the cecum, and the colon was measured immediately after slaughter (Accumet Basic; Fisher Scientific, Pittsburgh, PA). Cecal samples (20 g) were also collected at slaughter and mixed with 2 *N* HCl in a 1:1 ratio and these samples were stored at –20°C until analyzed for VFA.

Chemical and Physical Analysis

Diets and ingredients were analyzed for GE using bomb calorimetry (model 6300; Parr Instruments, Moline, IL), DM (method 930.15; AOAC Int., 2007), CP by combustion (method 999.03; AOAC Int., 2007) on a Rapid N cube apparatus (Elementar Americas Inc., Mt Laurel, NJ), and ash (method 942.05; AOAC Int., 2007). Acid hydrolyzed ether extract was determined by acid hydrolysis using 3 *N* HCl (Sanderson, 1986) followed by crude fat extraction using petroleum ether (method 2003.06; AOAC Int., 2007) on a Soxtec 2050 automated analyzer (FOSS North America, Eden Prairie, MN) and for AA (method 982.30 E (a, b, c); AOAC Int., 2007). The 4 samples of corn ground to different particle sizes were analyzed for total starch (Thivend et al., 1972), ADF (method 973.18; AOAC Int., 2007), and NDF (Holst, 1973), and P and Ca were analyzed by the inductively coupled plasma spectroscopy procedure (method 975.03; AOAC Int., 2007) after wet ash sample preparation (method 975.03; AOAC Int., 2007). All diets and ingredients were ground through a 1-mm screen in a Wiley mill (model 4; Thomas Scientific, Swedesboro, NJ) before analysis. All samples were analyzed in duplicate. The concentration of VFA in cecal samples was measured using the cecal sample that was preserved in HCl. Preparation of the cecal sample for VFA analysis was as described by Urriola and Stein (2010) except that 2 mL of the cecal digesta–HCl mixture was mixed with 8 mL of distilled water. The procedures to determine VFA were described by Erwin et al. (1961) and Urriola and Stein (2010). Loose bulk density and filling angle of repose of ingredients and diets were determined as described by Cromwell et al. (2000) and Appel (1994), respectively. Surface area of ingredients was determined as described by Kim et al. (2002). The surface area was calculated using the mean particle size of the grain as a reference.

Calculations and Statistical Analysis

At the conclusion of the experiment, data for feed intake and BW were summarized to calculate ADG, ADFI,

Table 3. Physical composition of experimental diets, as-fed basis[1]

	Corn particle size, µm														
	Phase 1				Phase 2				Phase 3					*P*-value[2]	
Item	865	677	485	339	865	677	485	339	865	677	485	339	SEM	Linear	Quadratic
Filling angle of repose,°	47.1	48.8	50.6	54.8	46.0	49.2	52.1	54.0	46.6	48.1	51.3	54.5	0.6	<0.01	0.036
Loose bulk density, g/L	713	696	667	645	704	690	670	631	702	683	661	627	8.6	<0.01	0.564

[1]Data are least squares means of 3 observations per treatment.

[2]The *P*-values represent the data for phase 1. The *P*-values for phases 2 and 3 are not shown but the follow the same trend as phase 1.

and G:F for each pig within each phase and overall for each sex and diet. The overall G:F based on HCW was calculated by subtracting the HCW of pigs at the start of the experiment from the HCW of pigs at slaughter to calculate carcass ADG, and carcass ADG was then divided by the overall ADFI. The HCW at the start of the experiment was calculated from Kil et al. (2013).

All data except physical characteristics of feed samples were analyzed as a 2 × 4 factorial with sex and diet as factors using the MIXED procedure (SAS Inst. Inc., Cary, NC). The model included sex, particle size, and the sex × particle size interaction as fixed effects and block as the random effect. However, interactions between diet and sex were not significant for the response variables analyzed, except for ADFI from d 0 to 29 and G:F from d 29 to 58 and from d 0 to 93. Therefore, the interaction was removed from the final model and only the main effects of sex and particle size were included for the variables that had no interaction. For variables with interaction, interaction was included in the model and results for both gilts and barrow were calculated separately. Growth performance data were analyzed as repeated measures for the 3 phases using ar(1) as the covariate parameter. Homogeneity of variances was confirmed using the HOVTEST of SAS. Outliers were determined using the UNIVARIATE procedure of SAS. Least squares means were used to calculate mean values for each independent variable. Linear and quadratic contrasts were used to analyze effects of reducing corn particle size on response variables. Appropriate coefficients for unequally spaced particle sizes of corn were determined using the interactive matrix language procedure in SAS. Data for physical characteristics of feed samples were analyzed using the MIXED procedure with subsample as the experimental unit. Linear and quadratic contrasts were also used to analyze effects of reducing the corn particle size on physical characteristics of feed samples for each phase. Data for stomach morphology were compared using the χ^2 (PROC FREQ of SAS), but the average of the lesions of the stomach was analyzed using the MIXED procedure. The pig was the experimental unit for all analyses except the analysis for physical characteristics of feed samples, and an α-value of 0.05 was used to assess significance among means. If *P*-values were >0.05 but <0.10, differences were considered tendencies.

RESULTS

One pig fed the diet containing corn with a particle size of 677 µm was removed from the experiment in the second phase because this pig developed a belly abscess. All other pigs remained in good health throughout the experiment and all pigs readily consumed their assigned diets.

Filling angle of repose increased ($P < 0.05$) and bulk density was reduced ($P < 0.05$) as the corn particle size was reduced (Table 3). This was true for diets used in all 3 phases.

Growth Performance and Ulcer Development

The starting weight and the final weight in each of the 3 phases were not different among dietary treatments (Table 4). Likewise, differences among treatments were not observed for ADG in any of the 3 phases or for the overall period. In phase 1, ADFI of gilts increased (linear, $P < 0.01$) as the particle size of corn decreased, but for barrows, no effect of the particle size was observed (interaction, $P < 0.05$). However, no differences among treatments were observed for ADFI during phase 2 and for the overall experimental period, but the ADFI for phase 3 increased (linear, $P < 0.05$) as the particle size of corn was reduced, regardless of the sex of the animals

The G:F for phase 1 decreased (linear, $P < 0.05$) as the particle size of corn was reduced. In phase 2 and over the entire experimental period, G:F of gilts also decreased (linear, $P < 0.01$) as the particle size of corn was reduced, but for barrows, no differences among treatments were observed (interaction, $P < 0.05$). During the third phase, no effects of particle size on G:F were observed regardless of the sex. If G:F was calculated based on HCW, there were no differences among dietary treatments, regardless of the sex of the animals.

Initial BW was greater ($P < 0.01$) in barrows than in gilts. Likewise, barrows had greater ($P < 0.01$) final

Table 4. Growth performance of pigs fed diets containing corn ground to different particle sizes[1]

	Corn particle size, μm					*P*-value		*P*-value			
Item	865	677	485	339	Pooled SEM	Linear *P*-value	Quadratic *P*-value	Barrows	Gilts	Pooled SEM	*P*-value
BW, kg											
Day 0	31.97	31.94	32.19	32.00	0.44	0.468	0.639	32.57	31.48	0.27	<0.01
Day 29	62.81	62.09	62.33	61.86	1.18	0.396	0.838	64.88	59.67	0.58	<0.01
Day 58	94.72	94.08	93.83	93.72	2.16	0.533	0.852	99.38	88.80	0.98	<0.01
Day 93	129.97	128.40	130.25	129.81	2.90	0.885	0.753	136.24	122.98	1.41	<0.01
ADG, kg/d											
Day 0 to 29	1.03	1.01	1.00	0.99	0.03	0.296	0.793	1.07	0.94	0.01	<0.01
Day 29 to 58	1.06	1.07	1.05	1.06	0.04	0.804	0.932	1.15	0.97	0.02	<0.01
Day 58 to 93	1.01	0.98	1.04	1.03	0.17	0.291	0.711	1.05	0.98	0.02	<0.01
Day 0 to 93	1.03	1.02	1.03	1.03	0.03	0.969	0.763	1.09	0.96	0.01	<0.01
ADFI, kg/d											
Day 0 to 29[2]											
Gilts	1.88	1.94	1.95	2.10	0.06	<0.01	0.418	–	–	–	–
Barrows	2.33	2.32	2.30	2.20	0.07	0.159	0.432	–	–	–	–
Day 29 to 58	3.01	3.01	3.05	3.11	0.12	0.269	0.703	3.35	2.74	0.05	<0.01
Day 58 to 93	3.24	3.31	3.44	3.47	0.12	0.037	0.854	3.63	3.10	0.06	<0.01
Day 0 to 93	2.81	2.85	2.90	2.94	0.10	0.089	0.975	3.12	2.63	0.04	<0.01
G:F											
Day 0 to 29	0.49	0.47	0.47	0.46	0.01	0.027	0.521	0.47	0.48	0.01	0.377
Day 29 to 58[2]											
Gilts	0.37	0.37	0.36	0.33	0.01	<0.01	0.026	–	–	–	–
Barrows	0.34	0.34	0.33	0.36	0.01	0.572	0.194	–	–	–	–
Day 58 to 93	0.31	0.30	0.30	0.30	0.01	0.186	0.312	0.29	0.32	0.01	<0.01
Day 0 to 93[2]											
Gilts	0.38	0.37	0.37	0.35	0.01	<0.01	0.417	–	–	–	–
Barrows	0.36	0.34	0.35	0.36	0.01	0.851	0.109	–	–	–	–
Day 0 to 93,[3] HCW	0.28	0.28	0.28	0.28	0.01	0.174	0.438	0.28	0.28	0.01	0.411

[1]Data are means of 18 observations per particle size treatment, except for the treatment with a corn particle size of 677 μm, which had only 17 observations. For sex, data are means of 36 observations for males and 35 observations for females.

[2]Particle size × sex interaction ($P < 0.05$).

[3]The G:F was calculated based on HCW.

BW at the end of each of the 3 phases than gilts and the ADG was greater ($P < 0.01$) for barrows in each of the 3 phases and for the overall experiment than for gilts. The ADFI was also greater ($P < 0.01$) for barrows than for gilts for phases 2 and 3 and for the overall experiment, but gilts had greater ($P < 0.01$) G:F than barrows for phase 3, but this was not the case for phase 1.

There were no sex effects observed in stomach morphology, therefore, only the main effect of corn particle size is shown in Table 5. There were no incidences of ulcers in the stomach of pigs regardless of dietary treatment. However, the incidences of total stomach parakeratosis increased ($P < 0.01$) as the particle size of corn decreased, but minor or medium incidences of parakeratosis were not different among treatments. In contrast, major parakeratosis and average stomach score were greater ($P < 0.05$) in pigs fed corn ground to a finer particle size than in pigs fed corn ground to a coarser particle size.

Carcass Characteristics

There were no differences in live BW, carcass fat-free lean (**FFL**), or HCW among dietary treatments (Table 6), but dressing percentage increased (linear, $P < 0.01$) as the corn particle size decreased. Values for back fat depth, LEA, and pH of LEA were not different among dietary treatments, but total organ weight as a percentage of HCW decreased (linear, $P < 0.01$) as the corn particle size was reduced. The weight of the empty intestine also decreased (linear, $P < 0.01$) as the corn particle size was reduced, but no differences in the weights of the liver, heart, kidney, spleen, or stomach were observed among dietary treatments.

Live BW was less ($P < 0.01$) in gilts than in barrows and HCW, dressing percentage, and back fat depth were also less ($P < 0.01$) in gilts than in barrows. However, no differences were observed for LEA and pH of LEA, but FFL and organ weight as a percentage of HCW were greater ($P < 0.01$) for gilts than for

Table 5. Stomach morphology from finishing pigs fed diets containing corn ground to different particle sizes[1]

	Corn particle size, µm				Pooled	
Item	865	677	485	339	SEM	P-value
Normal, %	50.00	29.41	5.56	0.00	–	<0.01
Minor parakeratosis, %	33.33	64.71	61.11	44.44	–	0.206
Medium parakeratosis, %	16.67	0.00	22.22	22.22	–	0.223
Major parakeratosis, %	0.00	5.88	11.11	33.33	–	0.016
Average stomach score[2]	0.67	0.80	1.39	1.89	0.19	<0.01

[1]Data are means of 18 observations per treatment, except for the treatment with a corn particle size of 677 µm, which had only 17 observations. Data are expressed as a frequency of incidence of parakeratosis in the esophageal region in the stomach of the pig.

[2]Scoring system ranged from 0 to 3, where a score of 0 means no evidence of lesions, a score of 1 means minor parakeratosis, a score of 2 indicates medium parakeratosis, and a score of 3 indicates parakeratosis.

barrows. Organs were heavier ($P < 0.01$) in barrows than in gilts except for spleen and total empty intestine, where differences were not observed.

pH and Volatile Fatty Acid Concentration

The pH in the stomach and ileal contents were not affected by treatments, but the pH in the cecal and colon contents increased (linear, $P < 0.01$) as the particle size of corn was reduced (Table 7). In contrast, the concentration of acetate, propionate, and butyrate in cecal contents was reduced (linear, $P < 0.01$) as the corn particle size was reduced.

The pH in the stomach, ileum, cecum, and colon were not different between barrows and gilts. Likewise, no differences were observed in the concentration of acetate, propionate, and butyrate.

DISCUSSION

Physical Characteristics of Diets

The filling angle of repose and bulk density are considered indirect indicators of feed flowability and feed compaction, respectively (Appel, 1994; Cromwell et al., 2000). The filling angle of repose is the angle at which a pile of material maintains its slope without falling apart and it is affected by the physical properties of feed materials such as shape, particle size, and porosity (Lawrence et al., 2003; Rosentrater, 2012). Bulk density represents the amount of feed material that can be stored in bins, containers, and feeders that have a specific volume (Rosentrater, 2012). Therefore, both, filling angle of repose and bulk density are important measurements that need to be considered when the particle size of cereal grains are modified. A greater filling angle of repose indicates that there is reduced flowability of the feed material and a lower value for bulk density means that less feed material can be stored per volume unit. The reduction in bulk density that was observed as the particle size of diets was reduced indicates that less feed material can be stored in a given bin or feeder if corn is ground to a smaller particle size. An increase in the filling angle of repose in diets containing SBM or distillers' dried grains with solubles with a finer particle size haS been reported (Lawrence et al., 2003; Liu et al., 2012) and the current data for corn support the observations with SBM and distillers' dried grains with solubles. This indicates that there is a poorer flowability of diets if corn, SBM, or distillers' dried grains with solubles is ground to a finer particle size than to a coarser particle size.

Growth Performance and Ulcer Development

The observation that there were no differences in growth performance among dietary treatments if the data were corrected for HCW indicates that the amount of added fat could be reduced if corn is ground to a finer particle size and if diets are formulated to a constant ME. It is likely that the difference in the overall G:F observed in gilts is the result of differences in gut fill because HCW of gilts was not different among treatments. It is possible that the increased fermentation of starch in the hindgut of gilts fed diets containing corn ground to a larger particle size has contributed to this difference as indicated by the increased VFA concentration in cecal contents. However, if diet energy concentration is allowed to change as the particle size of corn is reduced with no adjustments in dietary fat additions, there is a reduced ADFI and increased G:F in pigs fed corn ground to 400 µm compared with pigs fed corn ground to 1,000 µm (Wondra et al., 1995a). This is likely a result of the greater energy value in corn ground to 400 µm compared with corn ground to 1,000 µm (Wondra et al., 1995a). Improvements in G:F were also observed if finishing pigs were fed wheat that was ground to 600 µm compared with pigs fed wheat ground to 1,300 µm (Mavromichalis et al., 2000). A similar observation was made when growing–finishing pigs were fed sorghum-based diets in which the particle size was reduced from 724 to 319 µm (Paulk et al., 2015). In contrast, growth performance of pigs fed SBM that was ground to 639 or 444 µm was not different from that of pigs fed SBM ground to 965 or 1,226 µm (Lawrence et al., 2003). It was hypothesized that the reason for this observation is the relatively low inclusion level of SBM in the diet (Lawrence et al., 2003). Therefore, the effect of reduced particle size may be measurable only if a high inclusion rate of the ingredient is used in the diet.

The esophageal region is the region in the pig stomach that has the greatest risk of developing gastric ulcers when pigs are fed ingredients with a reduced

Table 6. Weights of carcass and body components of growing pigs fed diets containing corn ground to different particle sizes[1]

Item	Corn particle size, μm				Pooled	*P*-value					
	865	677	485	339	SEM	Linear *P*-value	Quadratic *P*-value	Barrows	Gilts	Pooled SEM	*P*-value
Live wt,[2] kg	127.45	126.96	127.35	127.38	2.88	0.964	0.830	133.70	120.74	1.42	<0.01
HCW, kg	101.10	101.30	101.67	102.31	2.44	0.573	0.827	107.35	95.76	1.15	<0.01
Dressing percentage,[3] %	79.30	79.78	79.82	80.29	0.31	<0.01	0.962	80.27	79.32	0.17	<0.01
Back fat depth, cm	2.23	2.22	2.48	2.25	0.19	0.493	0.534	2.69	1.88	0.09	<0.01
LEA,[4] cm²	54.52	53.44	51.32	52.92	1.43	0.191	0.364	52.46	53.65	0.89	0.346
pH of LEA[5]	5.60	5.57	5.63	5.62	0.03	0.372	0.730	5.63	5.58	0.02	0.074
FFL,[6] %	53.29	53.06	51.71	52.74	0.99	0.284	0.497	50.68	54.77	0.49	<0.01
Organ wt, % of HCW	6.43	6.07	6.06	5.78	0.12	<0.01	0.787	5.92	6.25	0.08	<0.01
Organ wt, kg											
Liver	1.81	1.78	1.76	1.74	0.05	0.260	0.852	1.83	1.71	0.03	<0.01
Heart	0.48	0.51	0.49	0.47	0.02	0.464	0.084	0.51	0.47	0.01	<0.01
Kidney	0.44	0.46	0.47	0.45	0.01	0.221	0.124	0.47	0.44	0.01	<0.01
Spleen	0.18	0.17	0.19	0.18	0.01	0.153	0.721	0.18	0.19	0.01	0.085
Stomach	0.56	0.56	0.55	0.55	0.02	0.454	0.903	0.57	0.54	0.01	0.162
Empty intestine	3.01	2.65	2.72	2.52	0.11	<0.01	0.372	2.80	2.64	0.06	0.076

[1]Data are means of 18 observations per particle size treatment, except for the treatment with a corn particle size of 677 μm, which had only 17 observations. For sex, data are means of 36 observations for males and 35 observations for females.

[2]Live weight was measured after an overnight fast.

[3]Dressing percent = HCW/live wt × 100.

[4]LEA = loin eye area.

[5]The pH was measured at the 10th rib in the loin eye (longissimus dorsi).

[6]FFL = carcass fat-free lean.

particle size because of the lack of protective mucus in the esophageal region (Mahan et al., 1966; Maxwell et al., 1970; Varum et al., 2010). Pigs fed corn ground to 1,200 μm have fewer ulcers and less keratinization in the esophageal region compared with pigs fed corn ground to 400 μm (Wondra et al., 1995a). In sows, development of ulcers and parakeratosis increases as the particle size of corn decreases from 1,200 to 400 μm (Wondra et al., 1995c) or if a pelleted diet is fed instead of a mash diet (Hancock and Behnke, 2001). The greater average stomach score observed as the corn particle decreased had no effect on pig growth performance. This concurs with observations indicating that G:F was not affected in pigs fed diets containing wheat ground to 600 μm even though those pigs had more parakeratosis in the esophageal region compared with pigs fed diets containing wheat ground to 1,300 μm (Mavromichalis et al., 2000). However, parakeratosis may develop into ulcers if pigs are stressed as is often the case in commercial production systems (Ramis et al., 2004).

Carcass Characteristics

The increase in dressing percentage that was observed as pigs were fed diets containing corn ground to a smaller particle size is partly due to a reduction in the intestinal weight. This observation is in agreement with data by Wondra et al. (1995a) and indicates that a greater proportion of diet energy and nutrients is directed toward carcass tissue synthesis compared with synthesis of intestinal tissue. The lack of an effect of corn particle size on FFL is in agreement with data indicating that wheat ground to either 1,300 or 600 μm has no effect on FFL (Mavromichalis et al., 2000).

pH and Volatile Fatty Acid Concentration

The lack of an effect of corn particle size on the pH in the stomach and ileal contents is in agreement with values reported by Kim et al. (2009) and is likely a result of the fact that most VFA is synthesized in the hindgut. The increase in the pH of the cecal and colon contents that was observed as the corn particle size was reduced is possibly related to the lower concentration of VFA in the cecal contents as the corn particle size decreased. This observation concurs with data reported in lupins ground to different particle sizes (Kim et al., 2009) and is likely a result of less fermentation taking place in the hindgut of pigs fed the diets containing corn ground to smaller particle sizes compared with corn ground to greater particle sizes (Callan et al., 2007). The apparent ileal digestibility of starch is increased as the particle size of corn is reduced (Rojas and Stein, 2015), which, in turn, results in less substrate for the microbes

Table 7. The pH in contents of the stomach, ileum, cecum, and colon and concentration of VFA in cecal contents from finishing pigs fed diets containing corn ground to different particle sizes[1]

	Corn particle size, µm					*P*-value		*P*-value			
Item	865	677	485	339	Pooled SEM	Linear *P*-value	Quadratic *P*-value	Barrows	Gilts	Pooled SEM	*P*-value
pH[2]											
Stomach	4.86	4.99	4.50	4.12	0.42	0.097	0.396	4.73	4.51	0.26	0.555
Ileum	6.74	6.86	6.87	6.82	0.09	0.439	0.273	6.83	6.81	0.05	0.790
Cecum	6.04	6.20	6.54	6.64	0.09	<0.01	0.950	6.36	6.36	0.06	0.979
Colon	5.85	5.94	6.20	6.25	0.08	<0.01	0.900	6.10	6.01	0.05	0.154
Short-chained fatty acids, µg/mL in cecal contents											
Acetate	2,537	2,286	1,973	1,846	136	<0.01	0.794	2,206	2,113	85	0.436
Propionate	872	794	690	617	48	<0.01	0.869	768	720	29	0.243
Butyrate	702	611	391	226	57	<0.01	0.224	518	447	34	0.144

[1]Data are means of 18 observations per particle size treatment, except for the treatment with a corn particle size of 677 µm, which had only 17 observations. For sex, data are means of 36 observations for males and 35 observations for females.

[2]The pH was measured immediately after slaughter.

of the hindgut to ferment. Fermentation in the hindgut is, therefore, reduced as the corn particle size is reduced, which is also demonstrated by the reduction in VFA concentration and the increase in the cecal and colonic digesta pH that was observed as the corn particle size was reduced. An increase in intestinal weight as a result of increased fiber in diets was also reported by Kass et al. (1980), and this is likely a result of increased microbial activity and fermentation in the hindgut of pigs fed diets containing corn ground to a coarser particle size.

Conclusions

The growth performance of barrows obtained in this experiment confirmed the hypothesis that inclusion of dietary fat may be reduced if corn is ground to a smaller particle size and also indicated that the dressing percentage is improved if diets containing corn ground to a reduced particle size are used. However, results indicated that gilts were not able to compensate for the reduced concentration of dietary fat if fed a diet containing corn ground to a smaller particle size the same way as barrows were, which may have been a result of increased gut fill. The current data also indicate that concentration of VFA in the hindgut of pigs is reduced and the pH is increased if corn ground to a smaller particle size is included in the diet. Although pigs fed diets containing corn ground to a smaller particle size developed some level of parakeratosis, this did not affect G:F based on HCW. However, responses of pigs to reducing the particle size should be investigated in commercial production systems, where pigs may be more stressed compared with pigs housed on research farms. Diets containing corn ground to a smaller particle size may also have poorer flowability than diets ground to a greater particle size.

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