Final Report to the Minnesota Pork Board

I. Project Title: Effect of diet composition and particle size on nutrient excretion of finishing pigs and the propensity to cause manure pit foaming

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II. Abstract

Manure pit foaming on commercial swine farms has been a significant problem in recent years. We hypothesize that dietary changes in fiber fermentability and lipid composition may alter manure chemical composition resulting in a greater risk of manure foaming due to methane production and foam stabilization from undigested lipids in anaerobic manure pits. The objective of this experiment was to measure nutrient excretion and manure foaming capability (MFC) of pigs fed 3 diets differing in the source and amount of neutral detergent fiber (NDF; % DM) and ether extract (EE; % DM) when ground to 2 particle sizes. Two groups of 24 growing gilts (initial BW =119.5 ± 8.9 kg) were placed into metabolism crates and randomly allotted to 1 of 6 diets (4 replicates/treatment/group). Dietary treatments consisted of 1) corn-soybean meal (7.2% NDF, 4.6% EE; CSB), 2) CSB + 35% DDGS (13.7% NDF, 6.2% EE; DDGS), and 3) CSB + 21% soybean hulls (20.0% NDF, 6.8% EE; SBH). Diets were ground to a mean particle size of 374 ± 29 µm (fine) or 631 ± 35 µm (coarse) and fed for 7 weeks. Excretion of DM, NDF, and EE were measured after total feces and urine were collected from d-21 to d-24. Except for d 21 to 24, all other feces and urine were collected and mixed daily and stored in simulated deep pit storage tanks. The MFC of each manure sample was measured in duplicate in the laboratory using a column and injecting nitrogen to stimulate foam production. Data were analyzed using the MIXED procedure of SAS, with individual pig as a random effect and diet composition, particle size, and their interaction as fixed effects. There was a diet composition × particle size interaction for MFC ($P < 0.05$). Greater ($P < 0.05$) MFC was observed for pigs fed coarse SBH compared with fine CSB and SBH, but not for fine or coarse DDGS. There was no diet composition × particle size interaction for excretion of DM, NDF, or EE. Excretion of DM and NDF were greater ($P < 0.05$) in pigs fed DDGS and SBH than in pigs fed CSB. Excretion of EE was greater ($P < 0.01$) for pigs fed DDGS than CSB or SBH. Excretion of DM, NDF, and EE was greater ($P < 0.05$) for coarse compared to fine diets regardless of the fiber composition. These results indicate that fiber composition in soybean hulls has a greater impact on MFC than the fiber composition in DDGS, and larger diet particle size reduces DM, NDF, and EE digestibility causing increased content in manure and MFC.

III. Introduction

Manure pit foaming on commercial swine farms has been a significant problem in recent years (Burns, 2010; Jacobson and Schmidt, 2010; Schmidt and Jacobson, 2010; Schmidt, 2011; UM, 2009; UM, 2010). Two of the most obvious problems caused by foaming manure are dirty pigs and reducing manure pit storage volume. Of even greater concern is that hydrogen sulfide gas is trapped in this foam, and when it is released, barn concentrations can easily exceed Occupational Safety and Health Administration permissible exposure limits (DOL, 2010), which are lethal to pigs and humans. Methane gas is also trapped in this foam. Methane is flammable and has been implicated as the underlying cause of several barn explosions (referred to as flash fires) in Minnesota, Iowa, and Illinois (Dehdashti, 2009; Jordahl, 2010; RAM, 2009; Vansickle, 2010; Willette, 2010). This has caused significant concern related to the health and safety of barn workers and pigs housed in these facilities.

Production and accumulation of foam in swine manure pits appears to be due to 3 main factors: production of biogas, presence of a surfactant, and presence of a stabilizer of foam. Indigestible nutrients excreted in feces of pigs may supply the necessary compounds that contribute to these 3 factors. Based on preliminary evidence from the University of Minnesota, incomplete digestion of dietary lipids may serve as the surfactant to initiate foaming, and undigested dietary fiber and hydrophobic particles may stabilize the foam bubbles (Hu, personal communication). In addition, a high concentration of fiber in manure can be fermented in anaerobic pits and increase biogas production (Carter et al., 2011; Spiehs et al., 2012).

The influence of lipids and fiber on the formation and stability of foam appears to be dependent on the particle size and concentration of lipids and fiber in swine diets. Hydrophobic particles entering the air-water surfaces of the foam can cause an increase or decrease in foam stability (Horozov, 2008). Finishing pigs fed diets with finer particle size had greater digestibility of lipids and fiber, resulting in less excretion in feces than when pigs are fed diets with larger particle size (Wondra et al., 2009). Therefore, changes in particle size, and subsequent changes in nutrient excretion in manure of pigs, may cause an increase in the formation and accumulation of foam in manure pits. To better understand the effect of diet composition on manure foaming capability, our research group at the University of Minnesota and USDA-ARS conducted a study to determine if these dietary factors may contribute to manure foaming capability.

IV. Objectives

To evaluate of the effect of dietary fiber fermentability, lipid composition and particle size on nutrient excretion and manure foaming in finishing pigs.

V. Procedures

The experimental design and procedures used in this study were reviewed and approved by the Institutional Animal Care and Use Committee at Iowa State University (Ames, IA).

Animal Management

This experiment was conducted over two 49-d periods at the Iowa State University Swine Nutrition Farm (Ames, IA). Two groups of 24 (n = 48; BW = 119.5 ± 8.9 kg) gilts, which were offspring from PIC Camborough (Pig Improvement Company, Hendersonville, TN), were moved into an environmentally controlled metabolism room and individually placed in metabolism crates (1.2 × 2.4 m) that allowed for separate collection of feces and urine. Ambient temperature in the metabolism room was maintained at approximately 21°C, and lighting was provided continuously. Crates were equipped with a stainless steel feeder and a nipple waterer to provide the pigs with *ad libitum* access to water. Gilts were randomly allotted to 1 of 6 diets, resulting in 4 replications for pigs per treatment per group.

Diets

Dietary treatments consisted of 1) corn-soybean meal (CSB), 2) CSB + 35% Distiller's dried grains with solubles (DDGS), and 3) CSB + 21% soybean hulls (SBH; Table 1). After ingredient proportioning and mixing, the entire diets were ground in a hammer mill to achieve the desired particle size. The distribution and standard deviation of the size of particles were analyzed in 13 sieve stack with automatic shaker (Table 2). The actual particle size for each diet was 352 μm (fine) and 675 μm (coarse; Table 3). All diets were fed in meal form. Pigs were fed twice daily a total amount of feed equivalent to 3.0% of their BW for 7 weeks, which approximates *ad libitum* feed intake for this size of pig. Actual feed disappearance was calculated from feed added minus feed not consumed.

Sample Collection

Samples of diets were collected and ground through a 1-mm screen before energy and nutrient analyses. During the d-21 to d-24 total collection period, stainless steel wire screens and stainless steel buckets containing 30 mL of 6 N HCl were placed under each metabolism crate to allow collection of all feces and urine of pigs. Feces and urine were collected twice daily before each meal, weighed, and stored at -20 °C until the end of all collections. Subsamples of feces from each pig were pooled, dried in force air oven at 60 °C, weighed, ground to pass through a 1 mm screen, and mixed to collect a representative sample for analysis. Energy and nutrient digestibility was calculated by using this portion of the feces. Meanwhile, urine samples were thawed, weighed, and pooled within pig to collect a representative sample for analysis. Energy and nutrient balance was calculated by using this portion of the urine.

Except for d-21 to d-24, fecal and urine output were collected twice daily from each pig and added to 24 individual stainless steel manure storage tanks (61 cm high × 96.5 cm wide) for the manure composition and gaseous emission analysis portion of the experiment. Each manure tank was designed to provide a similar surface area compared that commonly present in conventional growing-finishing barns with deep pit manure storage systems used in the U.S. swine industry (0.75 m^2/pig). During this period of time, urine was added to the manure tanks twice daily without acidifying to reduce volatilization of urinary nitrogen. At the end of each trial, gas samples (provided 3 d for room cleanup to reduce background gases) and composite manure samples (after manual mixing and stirring) were collected from manure storage tanks. Clean and dry manure storage tanks may contain less concentration of bacteria and require longer time to reach peak fermentation. However, despite pumping manure in commercial manure pits, they contain residual manure that serve as inoculum for future manure pit fermentation. Therefore, manure storage tanks used in this study were emptied prior to collecting manure from the second group of pigs, but contained 7.5 cm depth of residual manure to serve as inoculum from the first group of pigs fed the same respective dietary treatments prior to adding manure collected from the second group of pigs.

Chemical Analysis and Calculations

Diet, feces, urine and manure samples were analyzed at various laboratories as described in Table 2. The analyzed composition of experimental diets is shown in Table 3. Particle size was determined on a 13 half-height sieve shaker (Tyler RoTap, Mentor, OH) as described by Baker and Herrman (2002), with data reported as micrometers on an as-is basis.

To determine DE and ME content, GE of the diets, feces, and urine samples were determined using an isoperibol bomb calorimeter (Model 1282, Parr Instrument Company, Moline, IL) with benzoic acid used as a standard. For urine energy determination, 1 mL of urine was added to 0.5 g of dried cellulose and subsequently dried at 50°C for 24 h before energy determination. Urine addition and subsequent drying was repeated 3 times, for a total of 3 mL of filtered urine, over a 72-h period before urinary GE determination. Urinary energy was determined by subtracting the energy contained in cellulose from the combined urine plus cellulose energy. All energy values are reported on a DM basis.

The concentration of ether extract (EE) in diets and feces was analyzed using petroleum ether and following official method 90.39 section A (AOAC International, 2005), while the concentration of neutral detergent fiber (NDF) was analyzed using a distillation and filtration apparatus described by Holst (1973)

The concentration of N, C and S in diets, feces, urine and manure were analyzed using a VarioMAX CNS analyzer (Elementar Analysensysteme GmbH, Hanau, Germany). Samples were volatilized using catalytic tube combustion. After removing unwanted substances of resultant gases, the target gases were converted to N_2, CO_2, and SO_2, separated from each other by adsorption columns, and after heating were measured using a thermal conductivity detector. Subsequently, apparent total tract digestibility (ATTD) of C, DM, EE, energy, NDF, N, and S of each diet were calculated using procedure described by Adeola (2001).

Manure volume was obtained by measuring the depth of each manure container at the end of the experiment. Manure temperature was measured using a thermocouple thermometer (Fluke 51-Series II, Fluke Corp., Everett, WA), Manure pH was measured using a pH meter (Corning Model 530 with Corning probe #476436, Corning Inc., Corning, NY). Manure samples for analysis were collected after mixing and stirring each tank with a 15 cm stainless steel propeller for 3 min at a speed of 850 rpm.

Manure ammonia was analyzed colorimetrically (Chaney and Marbach, 1962) using a Varian Cary 50 Spectrophotometer (Varian Analytical Instruments, Walnut Creek, CA). Briefly, approximately 2 g of mixed manure sample was pipetted into a 15 mL centrifuge tube which added 6 mL of 0.1 N HCl. After samples were vortexed, they were filtered to remove large particles. Subsequently, two 1 mL aliquots of the filtered samples were pipetted into microcentrifuge tubes and centrifuged at 20,000 × g for 20 min at 4°C. The supernatant was additionally filtered through a 0.2 µm syringe filter and frozen at -20°C until analyzed. All results are reported as ammonium-N.

Sulfide volatilization in air from the manure tanks was measure with a S^{2-} probe (Thermo Orion Meter 290A+, probe #9616) that was calibrated using a standard curve (five levels;

sodium sulfide dissolved in water). The concentrated solution was titrated immediately before use to determine its exact concentration. Briefly, 2 g of each manure sample was weighed into a 100 mL beaker and added 38 mL of de-aerated nanopure water, 40 mL of SAOB solution (sulfide antioxide buffer; Orion 941609, Thermo Fisher Scientific Inc.). The pH of the mixture was maintained at pH 12 in order to accurately measure S^{2-} using the probe. The calibrated probe was inserted into each beaker to record S^{2-} concentration. A control solution and blank were analyzed at the end of each test to check accuracy of probe operation.

All samples of manure were analyzed for foaming capability index which used the method adapted from Yan et al. (2014), which introduced air stone to create fine size and stable air bubbles. Briefly, each 25 mL manure sample was placed in a cylinder (volume = 100 mL; inner diameter = 2.54 cm). A 1 m length of transparent tubing with 2.54 cm inner diameter was used to reach a maximum detection limit of 450 mL for some samples. Each sample was aerated through a cylindrical air stone at 0.0033 L/s until a steady state height was reached. The manure foaming capacity (MFC) index was calculated as the height of foam produced divided by the initial foam level. Once aeration ceased, the final height of foam became the initial level and foam recession time was recorded. Each manure sample was measured in duplicate.

Statistical Analysis

The experiment was designed as a 3 × 2 factorial arrangement of treatments within a randomized complete block design, with the individual pig or manure container serving as the experimental unit. With 6 treatments and a total of 24 pigs utilized for each group, there were

4 replications per treatment per group, such that with two groups there were 8 replications per treatment. Data were analyzed using the MIXED procedure of SAS (SAS Inst. Inc., Cary, NC), with individual pig as a random effect and group, diet composition, particle size, and their interaction as fixed effects. Results are reported as least squares means. Comparisons among treatments were performed using the PDIFF option of SAS with the Tukey-Kramer adjustment for multiple comparisons. Treatment effects were considered significant if $P < 0.05$.

VI. Results and Discussion

Pig Growth Performance

Pigs in group 1 were housed at a slightly higher effective environmental temperature (23.3°C with 64.8% relative humidity) compared with pigs in group 2 (21.3°C with 65.5% relative humidity), but both environments were within the thermal neutral zone for pigs of this BW. All pigs in both groups were in good health and readily consumed experimental diets. There were no differences in overall ADFI among dietary treatments and group of pigs (Table 4).

Pigs in group 1 had greater ($P < 0.01$) initial BW (122.46 kg) than pigs in group 2 (166.52 kg). With this difference, a difference between in final BW, ADG and G:F between group 1 and group 2 was expected. There was no diet composition × particle size interaction for BW, ADG and G:F. However, pigs fed the fine particle size diets had greater ($P < 0.01$) final BW, ADG and G:F than pigs fed the coarse particle size diets. Pigs fed SBH had greater ($P = 0.04$) feed efficiency (G:F) than pigs fed DDGS (Table 4).

Physical characteristics of manure, gas production, manure chemical composition, and manure output

Hydrogen sulfide production and manure output measured from manure tanks were greater ($P < 0.05$) for pigs in group 2 than for pigs in group 1. However, there were no differences in manure foam characteristics (MFC or recession time) among pigs of the 2 groups (Table 5).

There was a diet composition × particle size interaction for MFC and recession time ($P < 0.05$). Greater MFC and recession time were observed for pigs fed coarse SBH compared fine SBH or fine CSB, but not for fine or coarse DDGS. Also, greater MFC and recession time was observed for pigs fed coarse CSB compared with fine CSB (Table 5).

There was no diet composition × particle size interaction for hydrogen sulfide gas (sulfide probe) and ammonia (NH_4-N). Pigs fed DDGS had greater ($P < 0.01$) hydrogen sulfide gas and ammonia gas production than pigs fed CSB and SBH. Pigs fed coarse particle size diets had greater ($P < 0.01$) ammonia gas production than those fed fine particle size diets (Table 5).

There was no diet composition × particle size interaction for manure output, manure tank temperature, and manure pH. Pigs fed SBH had lower manure pH than CSB ($P < 0.05$) and DDGS ($P < 0.01$). Pigs fed coarse particle size diets had lower ($P < 0.05$) manure pH than pigs fed fine particle size diets (Table 5).

There was no diet composition × particle size interaction for concentration of N, C, or S in manure. Pigs fed diets with DDGS had greater ($P < 0.01$) manure concentration of N and C compared with pigs fed SBM and SBH, while manure from pigs fed SBM had less ($P < 0.01$)

concentration of N and C than pigs fed SBH. Pigs fed coarse particle size diets had greater (P < 0.01) N and C concentrations in manure than pigs fed fine particle size diets. Pigs fed SBH had less (P < 0.01) S concentration in manure than those fed CSB and DDGS (Table 5).

Energy balance of diets

Gross energy content among diet samples varied from 4,278 to 4,519 kcal/kg DM. There was no diet composition × particle size interaction for DE and ME. Feeding the fine particle size diets resulted in greater (P < 0.01) DE and ME content than feeding coarse particle size diets (Table 6).

EE and NDF excretion and digestibility

Pigs in group 1 had higher (P < 0.05) DM, EE and NDF intake than pigs in group 2 (Table 6). There was no diet composition × particle size interaction for DM intake, feces excretion and digestibility. Pigs fed CSB had less DM excretion in feces and greater DM digestibility than DDGS (P < 0.01 and P < 0.01, respectively) and SBH (P < 0.05 and P < 0.01, respectively). Pigs fed fine particle size diets had less DM excretion in feces and greater DM digestibility than (P < 0.01) those fed coarse particle size diets (Table 6).

There was no diet composition × particle size interaction for EE intake and feces excretion. Pigs fed CSB had less (P < 0.01) EE intake than those fed DDGS and SBH. Pigs fed DDGS had greater (P < 0.01) EE excretion in feces than those fed CSB and SBH. Pigs fed fine particle size diets had less (P < 0.01) EE excretion in feces than those fed coarse particle size diets. There was a diet composition × particle size interaction for EE digestibility (P < 0.05). Greater EE digestibility was observed for pigs fed fine CSB and fine SBH compared with coarse CSB, coarse DDGS and coarse SBH. Also, less EE digestibility was observed for pigs fed coarse CSB compared with fine DDGS and coarse SBH (Table 6).

There was no diet composition × particle size interaction for NDF intake, feces excretion and digestibility. However, pigs fed SBH had greatest ($P < 0.01$) NDF intake compared with those fed CSB and DDGS, while pigs fed CSB had the least ($P < 0.01$) NDF intake compared with those fed DDGS and SBH. Pigs fed fine particle size diets had less NDF feces excretion and greater NDF digestibility ($P < 0.05$) than those fed coarse diets (Table 6).

N, C and S excretion and balance

Pigs in group 1 had higher ($P < 0.05$) N, C, and S intake than pigs in group 2 (Table 7). There was no diet composition × particle size interaction for N intake, feces excretion, digestibility, urine excretion and net N utilization. Pigs fed DDGS had greater ($P < 0.01$) N intake than those fed SBH, while pigs fed CSB had less ($P < 0.01$) N excretion in feces than those fed DDGS and SBH. Pigs fed SBH had less N digestibility and urine excretion than pigs fed CSB ($P < 0.01$ and $P < 0.01$, respectively) and DDGS ($P < 0.05$ and $P < 0.01$, respectively). Pigs fed fine particle size diets had less ($P < 0.05$) N excretion in feces and greater N digestibility ($P < 0.01$) than those fed the coarse diets (Table 7).

There was no diet composition × particle size interaction for C intake, feces excretion, digestibility and urine excretion. Pigs fed CSB had less C excretion in feces and greater C digestibility ($P < 0.01$) than pigs fed DDGS and SBH. Pigs fed SBH had less ($P < 0.01$) C urine excretion than those fed CSB and DDGS. Pigs fed fine particle size diets had less C excretion in feces and greater C digestibility than ($P < 0.01$) those fed the coarse diets (Table 7).

There was no diet composition × particle size interaction for S intake, feces excretion, digestibility and net S utilization. Pigs fed DDGS had greater S intake and less net S utilization than those fed CSB ($P < 0.01$ and $P < 0.05$, respectively) and SBH ($P < 0.01$ and $P < 0.01$, respectively). Pigs fed CSB had less S excretion in feces than those fed DDGS ($P < 0.05$) and SBH ($P < 0.01$). Pigs fed SBH had less S digestibility than pigs fed CSB ($P < 0.01$) and DDGS ($P < 0.05$). There was a diet composition × particle size interaction for S urine excretion ($P < 0.01$), where greater S excretion in urine was observed for pigs fed fine DDGS compared with fine CSB, coarse CSB, fine SBH and coarse SBH. Also, less S urine excretion was observed for pigs fed fine SBH compared with those fed fine CSB, coarse CSB and coarse DDGS (Table 7).

Summary of Implications

Feeding the coarsely ground SBH diet to finishing pigs increased MFC, but feeding coarse and fine DDGS diets did not increase MFC. Diet fiber composition may have greater effect on MFC than diet lipid composition. Dry matter excretion was a significant factor that contributed to MFC. There was no clear association observed between N, C, S balance and MFC. These results suggest that diet formulation strategies to maximize dry matter digestibility (e.g. reducing diet particle size) and reduce dry matter excretion, along with minimizing the amount coarsely ground SBH in diets will decrease manure foaming propensity in anaerobic manure pit in pig barns.

Table 1. Ingredient concentration, calculated chemical composition of experimental diets.

	Diets		
Ingredient	CSB[1]	DDGS[2]	SBH[3]
Ingredient, as-fed basis, %			
Corn	79.72	62.50	57.34
Soybean hulls			20.75
Soybean meal	18.00		16.80
Soybean oil	0.30		3.32
Distiller's dried grains with solubles		35.10	
Limestone	0.87	1.15	0.60
Monocalcium phosphate (21% P, 17% Ca)	0.41	0.10	0.49
Sodium chloride	0.35	0.35	0.35
Vitamin mix[4]	0.20	0.20	0.20
Trace mineral mix[5]	0.15	0.15	0.15
L-Lys-HCl		0.39	
L-Trp		0.03	
L-Thr		0.03	
Calculated chemical composition, DM basis			
ME, kcal/kg	3750	3742	3734
NE, kcal/kg	2852	2802	2801
Crude protein, %	17.10	17.04	17.00
N, %	2.74	2.73	2.72
S, mg/kg	1972	3630	1966

[1]CSB = corn - soybean meal diet.

[2]DDGS = corn - distiller's dried grains with soluble diet.

[3]SBH = corn - soybean meal - soybean hulls diet.

[4]Provided per kilogram of diet: vitamin A, 3,062.5 IU; vitamin D3, 350 IU; vitamin E, 25 IU; vitamin K, 1.5 mg; vitamin B12, 0.025 mg; riboflavin, 1.5 mg; niacin, 28 mg; and pantothenic acid, 13.5 mg.

[5]Provided Cu (as $CuSO_4$), 1.1%; Fe (as $FeSO_4$), 11.0%; I (as $Ca(IO_3)_2$), 200 ppm; Mn (as $MnSO_4$), 2.6%; Zn (as $ZnSO_4$), 11.0%; and Se (as Na_2SeO_3), 200 ppm.

Table 2. Methods of analysis.

Measurement	Method
Particle size[1]	13 half-height sieve shaker (Tyler RoTap, Mentor, OH) Baker and Herrman (2002)
C[1]	VarioMAX CNS analyzer (Elementar Analysensysteme GmbH, Hanau, Germany)
DM[1]	AOAC International (2005) official method 934.01
Ether extract[1]	AOAC International (2005) official method 920.39 (A), petroleum ether
GE[1]	Isoperibol bomb calorimeter (Model 1281; Parr Instrument Co., Moline, IL)
Manure tank temperature	Thermocouple thermometer (Fluke 51-Series II, Fluke Corp., Everett, WA)
N[1]	VarioMAX CNS analyzer (Elementar Analysensysteme GmbH, Hanau, Germany)
NDF[1]	Holst (1973)
NH_4-N[1]	Chaney and Marbach (1962) Varian Cary 50 Spectrophotometer (Varian Analytical Instruments, Walnut Creek, CA)
Manure pH[1]	pH meter (Corning Model 530 with Corning probe #476436, Corning Inc., Corning, NY)
S[1]	VarioMAX CNS analyzer (Elementar Analysensysteme GmbH, Hanau, Germany)
Sulfide probe[1]	S^{2-} probe (Thermo Orion Meter 290A+, probe #9616)
Foaming characteristics[2]	Yan (2014)

[1]Analyzed by USDA-ARS, Ames, IA.

[2]Analyzed by University of Minnesota, Saint Paul, MN.

Table 3. Analyzed particle size and nutrient composition of experimental diet diets based on corn and soybean meal (CSB), 35% distillers dried grains with solubles (DDGS), or 20% soybean hulls (SBH) that were fine or coarsely ground.

		Nutrient composition, DM basis				
Dietary treatment[1]	Particle size of diets, μm	GE, kcal/kg	N, %	C, %	S, %	Ether extract, %
CSB-fine	364	4,287	2.65	44.62	0.21	4.56
DDGS-fine	352	4,519	2.79	45.89	0.24	6.19
SBH-fine	408	4,427	2.66	45.47	0.22	6.70
CSB-coarse	615	4,278	2.57	44.71	0.20	4.70
DDGS-coarse	603	4,502	2.73	45.70	0.23	6.22
SBH-coarse	675	4,395	2.58	45.31	0.20	6.87

[1]CSB = corn - soybean meal diet, DDGS = corn – soybean meal – 35% distiller's dried grains with solubles diet, SBH = corn - soybean meal – 20% soybean hulls diet.

Table 4. Growth performance of pigs fed corn and soybean meal diets supplemented with corn distillers dried grains with solubles or soybean hulls, that were ground fine (374 ± 29 µm) or coarse (631 ± 35 µm), and fed for 49-d.

Dietary treatment[1]	Pigs	Initial BW, kg	Final BW, kg	ADG, kg	ADFI, kg	G:F
Group						
1	24	123[a]	165[a]	0.88[a]	2.94	0.30[a]
2	24	117[b]	154[b]	0.78[b]	2.92	0.26[b]
SEM		2	2	0.03	0.03	<.01
DC × PS interaction[2]						
CSB-fine	8	122	164	0.86	3.03	0.28
DDGS-fine	8	125	166	0.84	2.95	0.28
SBH-fine	8	117	162	0.92	2.89	0.32
CSB-coarse	8	112	150	0.77	2.86	0.27
DDGS-coarse	8	123	161	0.78	2.99	0.26
SBH-coarse	8	118	157	0.80	2.86	0.28
SEM		3	4	0.04	0.06	0.01
Diet composition						
CSB	16	117	157	0.81	2.94	0.27[ab]
DDGS	16	124	163	0.81	2.97	0.27[a]
SBH	16	118	159	0.86	2.87	0.29[b]
SEM		2	3	0.03	0.04	<.01
Particle size						
Fine	24	121	164[a]	0.87[a]	2.96	0.29[a]
Coarse	24	118	156[b]	0.78[b]	2.90	0.27[b]
SEM		2	2	0.03	0.03	<.01
Source of variation, *P*-value						
Group		0.01	<.01	<.01	0.66	<.01
DC × PS interaction[2]		0.14	0.32	0.81	0.17	0.63
Diet composition		0.03	0.23	0.36	0.25	0.03
Particle size		0.13	0.01	0.01	0.25	<.01

[1]CSB = corn - soybean meal diet. DDGS = corn - distiller's dried grains with soluble diet. SBH = corn - soybean meal - soybean hulls diet.

[2]DC × PS interaction = interaction effect between diet composition (DC) and particle size (PS).

[abc] Values within a column with different letters are different ($P < 0.05$).

Table 5. Manure characteristics of pigs fed corn and soybean meal diets supplemented with corn distillers dried grains with solubles or soybean hulls that were ground fine (374 ± 29 µm) or coarse (631 ± 35 µm) and fed for 49-d.

		Foaming characteristics		Gas production characteristics		Physical property			Chemical composition, as-is basis		
Dietary treatment[1]	Pigs	Manure foaming capability, %[2]	Recession time, s[3]	Sulfide probe, µmol/g	NH_4-N, µmol/g	Tank depth, cm	Tank temperature, °C	pH	N, %	C, %	S, %
Group											
1	24	142	28	0.32[a]	385.70	25.04[a]	16.59	7.90	0.54	3.41	0.09[a]
2	24	101	23	0.46[b]	377.03	33.58[b]	16.33	8.00	0.51	3.26	0.08[b]
SEM		20	5	0.02	13.35	0.77	0.25	0.06	0.02	0.11	<.01
DC × PS interaction[4]											
CSB-fine	8	44[a]	6[a]	0.32	346.49	28.13	16.38	8.15	0.41	2.31	0.09
DDGS-fine	8	130[abc]	27[abc]	0.48	411.79	31.13	16.56	8.17	0.55	3.29	0.09
SBH-fine	8	91[ab]	19[ab]	0.32	311.51	30.13	16.48	7.83	0.48	3.03	0.07
CSB-coarse	8	154[bc]	37[bc]	0.33	366.60	27.75	16.20	8.15	0.44	3.04	0.09
DDGS-coarse	8	124[abc]	24[abc]	0.50	475.15	29.00	16.28	7.83	0.68	4.67	0.1
SBH-coarse	8	186[c]	41[c]	0.39	376.64	29.75	16.89	7.62	0.57	3.70	0.08
SEM		23	6	0.03	18.70	1.34	0.30	0.10	0.03	0.18	<.01
Diet composition											
CSB	16	99	21	0.33[a]	356.55[a]	27.94	16.29	8.15[a]	0.43[a]	2.67[a]	0.09[a]
DDGS	16	127	26	0.49[b]	443.47[b]	30.06	16.42	8.00[a]	0.62[b]	3.98[b]	0.09[a]
SBH	16	139	30	0.35[a]	344.07[a]	29.94	16.68	7.72[b]	0.53[c]	3.36[c]	0.07[b]
SEM		18	4	0.02	13.85	0.95	0.27	0.07	0.02	0.13	<.01
Particle size											
Fine	24	88 [a]	17[a]	0.37	356.60[a]	29.79	16.47	8.05[a]	0.48[a]	2.87[a]	0.08
Coarse	24	155[b]	34[b]	0.41	406.13[b]	28.83	16.45	7.87[b]	0.56[b]	3.80[b]	0.09
SEM		16	4	0.02	11.79	0.95	0.25	0.06	0.02	0.10	<.01
Source of variation, *P*-value											
Group		0.20	0.45	<.01	0.66	<.01	0.12	0.32	0.17	0.35	0.02
DC × PS interaction[4]		0.01	<.01	0.64	0.37	0.75	0.18	0.24	0.14	0.12	0.53
Diet composition		0.14	0.23	<.01	<.01	0.22	0.15	<.01	<.01	<.01	<.01
Particle size		<.01	<.01	0.25	<.01	0.39	0.92	0.03	<.01	<.01	0.18

[1]CSB = corn - soybean meal diet. DDGS = corn - distiller's dried grains with soluble diet. SBH = corn - soybean meal - soybean hulls diet.

[2]The sample was aerated through a cylindrical air stone at 0.0033 L/s until a steady state height was reached. A foaming capacity index was calculated as the height of foam produced divided by the initial level.

[3]Once aeration ceased, the final height of foam became the initial level, recession time recorded.

[4]DC × PS interaction = interaction effect between diet composition (DC) and particle size (PS).

[abc] Values within a column with different letters are different ($P < .05$).

Table 6. Energy and nutrient digestibility and balance of pigs fed corn and soybean meal diets supplemented with corn distillers dried grains with solubles or soybean hulls that were ground fine (374 ± 29 µm) or coarse (631 ± 35 µm) and fed for 4-d total collection period (DM basis).

		Energy			DM			Ether extract			NDF		
Dietary treatment[1]	Pigs	GE, kcal/kg	DE, kcal/kg	ME, kcal/kg	Intake, g/d	Feces excretion, g/d	Digestibility, %	Intake, g/d	Feces excretion, g/d	Digestibility, %	Intake, g/d	Feces excretion, g/d	Digestibility, %
Group													
1	24	3953	3486	3378	2,629[a]	293	89	154.37[a]	50.97	66.27	356.58[a]	89.58	72.87
2	24	3953	3469	3358	2,375[b]	274	88	138.69[b]	46.98	65.57	316.99[b]	87.34	70.27
SEM		0	23	23	53	14	1	3.31	1.97	3.35	9.31	5.95	9.81
DC × PS interaction[2]													
CSB-fine	8	4,278[a]	3,949	3,824	2,640	210	92	123.97	30.26	75.60[a]	187.48	56.86	69.74
DDGS-fine	8	4,502[b]	3,993	3,853	2,538	275	89	157.98	47.64	69.60[ad]	344.45	93.49	72.51
SBH-fine	8	4,395[c]	3,864	3,760	2,388	278	88	164.01	35.32	78.00[a]	466.41	87.30	80.98
CSB-coarse	8	4,287[d]	3,796	3,672	2,441	251	90	111.36	55.43	50.38[b]	176.11	66.36	61.93
DDGS-coarse	8	4,519[e]	3,835	3,703	2,631	375	86	162.96	69.86	57.19[bc]	365.36	135.07	63.17
SBH-coarse	8	4,427[f]	3,798	3,688	2,372	312	87	158.91	55.33	64.74[cd]	483.91	91.67	81.11
SEM		0	39	40	89	24	1	5.61	3.33	2.22	15.75	10.06	3.20
Diet composition													
CSB	16	3,822[a]	3,456	3,345	2,540	230[a]	91[a]	117.66[a]	42.84[a]	62.99[a]	181.79[a]	61.61[a]	65.83[a]
DDGS	16	4,048[b]	3,513	3,391	2,584	325[b]	87[b]	160.47[b]	58.75[b]	63.39[a]	354.91[b]	114.28[b]	67.84[a]
SBH	16	3,989[c]	3,464	3,368	2,380	295[b]	87[b]	161.46[b]	45.32[a]	71.37[b]	475.16[c]	89.49[b]	81.04[b]
SEM		0	28	28	63	17	1	3.96	2.35	1.57	11.14	7.11	2.26
Particle size													
Fine	24	3,947[a]	3,537[a]	3,427[a]	2,522	254[a]	90[a]	148.65	37.74[a]	74.40[a]	332.78	79.22[a]	74.41[a]
Coarse	24	3,958[b]	3,419[b]	3,309[b]	2,481	313[b]	87[b]	144.41	60.20[b]	57.43[b]	341.79	97.70[b]	68.74[b]
SEM		0	23	23	51	14	1	3.24	1.92	1.28	9.09	5.81	1.85
Source of variation, *P*-value													
Group		1.00	0.61	0.56	0.01	0.38	0.51	0.01	0.20	0.72	0.02	0.78	0.36
DC × PS interaction[2]		< .01	0.59	0.69	0.28	0.34	0.65	0.32	0.74	0.01	0.54	0.16	0.30
Diet composition		<.01	0.32	0.53	0.07	<.01	<.01	<.01	<.01	<.01	<.01	0.32	0.53
Particle size		<.01	<.01	<.01	0.58	<.01	<.01	0.37	<.01	<.01	0.49	0.03	0.04

[1]CSB = corn - soybean meal diet. DDGS = corn - distiller's dried grains with soluble diet. SBH = corn - soybean meal - soybean hulls diet.
[2]DC × PS interaction = interaction effect between diet composition (DC) and particle size (PS).
[abcdef]Values within a column with different letters are different ($P < .05$).

Table 7. Nitrogen, carbon, and sulfur balance of pigs fed corn and soybean meal diets supplemented with corn distillers dried grains with solubles or soybean hulls that were ground fine (374 ± 29 µm) or coarse (631 ± 35 µm) and fed for 4-d total collection period (DM basis).

		N					C				S				
Group	Pigs	Intake, g/d	Feces excretion, g/d	Digestibility, %	Urine excretion, g/d	Net utilization[2], %	Intake, g/d	Feces excretion, g/d	Digestibility, %	Urine excretion, g/d	Intake, g/d	Feces excretion, g/d	Digestibility, %	Urine excretion, g/d	Net utilization[2], %
1	24	70.05^{a}	10.40	85.20	26.48	47.48	1189.88^{a}	129.39	89.16	28.78	5.72^{a}	1.36	76.41	1.79	44.69
2	24	63.36^{b}	9.28	85.02	25.26	45.27	1075.54^{b}	120.98	88.61	26.07	5.18^{b}	1.20	76.31	1.77	43.25
SEM		1.39	0.52	0.82	0.88	1.58	23.83	6.10	0.56	0.89	0.11	0.06	1.14	0.10	1.67
DC × PS interaction[3]															
CSB-fine	8	67.96	6.65	90.21	29.34	47.03	1180.18	83.76	92.91	29.03	5.38	1.03	80.82	1.95^{ad}	67.96
DDGS-fine	8	69.39	8.83	87.12	29.62	44.42	1159.99	122.32	89.34	31.49	5.73	1.19	79.06	2.52^{b}	69.39
SBH-fine	8	61.54	11.06	81.71	18.20	52.00	1081.67	120.36	88.67	22.50	4.88	1.38	71.19	1.02^{c}	61.54
CSB-coarse	8	64.67	8.27	87.23	27.60	44.74	1088.90	111.64	89.73	27.06	5.17	1.13	78.28	1.54^{ae}	64.67
DDGS-coarse	8	73.51	12.01	83.71	29.46	43.71	1207.27	172.05	85.79	31.07	6.26	1.48	76.38	2.29^{bd}	73.51
SBH-coarse	8	63.16	12.21	80.69	21.00	46.34	1078.26	140.99	86.86	23.39	5.29	1.45	72.43	1.34^{ce}	63.16
SEM		2.35	0.87	1.39	1.50	2.67	40.31	10.31	0.94	1.51	0.19	0.10	1.93	0.11	2.35
Diet composition															
CSB	16	66.32^{a}	7.46^{a}	88.72^{a}	28.47^{a}	45.89	1134.54	97.70^{a}	91.32^{a}	28.04^{a}	5.28^{a}	1.08^{a}	79.55^{a}	1.75^{a}	46.34^{a}
DDGS	16	71.45^{b}	10.42^{b}	85.42^{a}	29.54^{a}	44.07	1183.63	147.18^{b}	87.56^{b}	31.28^{a}	5.99^{b}	1.34^{b}	77.72^{a}	1.18^{b}	37.64^{b}
SBH	16	62.35^{b}	11.64^{b}	81.20^{b}	19.60^{b}	49.17	1079.97	130.68^{b}	87.77^{b}	22.94^{b}	5.09^{a}	1.42^{b}	71.81^{b}	2.41^{c}	47.93^{a}
SEM		1.66	0.62	0.99	1.06	1.89	28.50	7.29	0.67	1.07	0.14	0.07	1.36	0.10	2.18
Particle size															
Fine	24	66.30	8.85^{a}	86.35^{a}	25.72	47.82	1140.61	108.81^{a}	90.31^{a}	27.67	5.33	1.20	77.02	1.83	42.49
Coarse	24	67.11	10.83^{b}	83.87^{b}	26.02	44.93	1124.81	141.56^{b}	87.46^{b}	27.17	5.57	1.35	75.69	1.73	45.45
SEM		1.36	0.50	0.80	0.86	1.54	23.27	5.95	0.54	0.87	0.11	0.06	1.11	0.08	1.63
Source of variation, *P*-value															
Group		0.01	0.17	0.88	0.36	0.36	0.01	0.36	0.51	0.07	0.01	0.10	0.95	0.91	0.57
DC × PS interaction[3]		0.30	0.50	0.67	0.32	0.65	0.24	0.37	0.63	0.64	0.13	0.47	0.52	<.01	0.86
Diet composition		<.01	<.01	<.01	<.01	0.18	0.05	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01
Particle size		0.68	<.01	0.04	0.81	0.20	0.64	<.01	<.01	0.69	0.13	0.07	0.41	0.24	0.22

[1]CSB = corn - soybean meal diet. DDGS = corn - distiller's dried grains with soluble diet. SBH = corn - soybean meal - soybean hulls diet.

[2]Net utilization = intake - feces excretion - urine excretion / intake.

[3]DC × PS interaction = interaction effect between diet composition (DC) and particle size (PS).

[abcde] Values within a column with different letters are different (*P* < .05).

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