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Impact of distillers dried grains with solubles particle size on nutrient digestibility, DE and ME content, and flowability in diets for growing pigs[1]

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ABSTRACT: A study was conducted to determine the effect of particle size of distillers dried grains with solubles (DDGS) on DE and ME content, diet DM, energy, N, P digestibility, and diet flowability for growing pigs. One DDGS source was processed through an Urshel Commitrol mill or a hammer mill to achieve mean particle sizes of 818, 595, and 308 μm. The basal control diet consisted of 96.8% corn with supplemental minerals and vitamins. Three experimental diets were formulated by replacing 30% of corn from the basal diet with DDGS of different particle sizes. Thirty-six growing pigs (initial BW of 40 ± 1.13 kg) were assigned to 1 of 4 treatments in a randomized complete block design according to their BW block and housed in individual metabolic crates for a 9-d adaptation period followed by a 4-d total collection of feces and urine. Pigs were provided ad libitum access to water and fed an amount of their respective experimental diets equivalent to 3% of the initial BW of each pig. Feed, feces, and urine samples were analyzed for DM, GE, N, and P and used to calculate diet apparent total tract digestibility (ATTD).Gross energy was also used to calculate DE and ME of diets as well as the DE and ME content of corn and DDGS with different particle sizes. Diet drained and poured angles of repose were measured using a modified Hele-Shaw cell method to evaluate the diet flowability. Inclusion of 30% DDGS with an average particle size of 308 μm improved ($P < 0.05$) dietary ATTD of DM and GE as well as DE (4,006 vs. 3,783 kcal/kg DM) and ME (3,861 vs. 3,583 kcal/kg DM) compared with 818 μm DDGS. No differences ($P > 0.05$) were found in N and P digestibility among the 3 DDGS diets. The DDGS particle size of 595 μm had greater ($P < 0.05$) DE but not ME compared with 818 μm DDGS, and DE and ME were not different between 308 and 595 μm. Compared with a 595 or 818 μm DDGS, grinding DDGS to 308 μm reduced diet flowability as indicated by a greater ($P < 0.05$) drained angle of repose. These results suggested that for each 25 μm decrease in DDGS particle size from 818 μm to 308 μm, the ME contribution of DDGS to the diet is 13.46 kcal/kg DM, but diet flowability will be reduced.

Key words: diet flowability, distillers dried grains with solubles, growing pigs, metabolizable energy, nutrient digestibility, particle size

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INTRODUCTION

It is well documented that reducing particle size of feed ingredients improves nutrient digestibility, growth rate, and feed conversion in pigs (Lawrence, 1983; Goodband and Hines, 1988). Recently, Liu (2008) found that the particle size distribution of the distillers dried grains with solubles (**DDGS**) was highly variable with a mean particle size of 660 μm and a standard deviation of 440 μm. A study of Gaines and Kocher (2008) found that the dietary contribution of ME of corn in the finishing diets was decreased by approximately 6.6 kcal/kg for each 25 μm increase in particle size from 450 to 850 μm. Mendoza et al. (2010) reported that DE and ME content of corn DDGS can be improved by grinding to a reduced particle size but provided no information on the incremental improvements in DE and ME that can be expected for every incremental decrease in DDGS particle size.

Dietz et al. (2008) found that extrusion of diets containing DDGS may reduce N retention in growing

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pigs, but the effects of DDGS particle size on diet N digestibility and retention are still unknown. Fermentation of corn during ethanol production results in the release of a portion of the phytate-bound P, which in turn results in a greater digestibility of P in fermented feed ingredients than in corn (Cromwell, 1979; Pedersen et al., 2007; Noureddini et al., 2009). However, there are no data on the effect of DDGS particle size on apparent total tract digestibility (**ATTD**) of dietary P in growing pigs. In addition, although the particle size distribution has been used as an important indicator to evaluate the flowability of particulate materials, limited studies have investigated the effect of DDGS particle size on the diet flowability. Therefore, the current experiment was conducted to determine the effects of DDGS particle size on nutrient digestibility, DE and ME content, and flowability in diets for growing pigs.

MATERIALS AND METHODS

The University of Minnesota Institutional Animal Care and Use Committee approved all of the experimental protocols in this study.

Animals and Housing

Thirty-six barrows (initial BW 40 ± 1.13 kg) were housed individually in metabolism cages at the Southern Research and Outreach Center in Waseca, MN, to facilitate separate total collection of feces and urine. Pigs were allowed a 9-d period to adapt to their assigned diets followed by a 4-d period in which all feces and urine from each pig were collected. Pigs were fed a daily amount of feed equivalent to 3 times their maintenance energy requirements (about 3% of BW), equally divided into 2 feedings at 0800 and 1600 h during both the adaptation and collection period. Pig BW were determined on d 0. The amount of feed provided to animals was recorded at each feeding time. If there was any feed remaining from the previous feeding period, it was removed, weighed, and subtracted from the amount offered to determine average daily feed disappearance. Feeders were located at the front of each metabolism cage, and a nipple waterer was located at the side of the cage to provide pigs ad libitum access to water. Room temperature was maintained at 20 ± 1°C to meet the comfort needs of the pigs.

Distillers Dried Grains with Solubles Sourcing and Particle Size Processing

One DDGS source with an original average particle size of 818 μm was used in the experiment, and this particle size served as the greatest particle size treatment. This DDGS source was further processed through an Urschel Commitrol (Urschel Laboratories, Inc., Valparaiso, IN) with a 0060 cutter head to produce a medium particle size of approximately 600 μm and a hammer mill with a 3.97 mm screen to produce a fine particle size of approximately 300 μm. Particle size of DDGS samples were determined by the method described by American Society of Agricultural and Biological Engineers (ANSI/ASAE S319.4; ANSI/ASAE, 2008). The final average particle size of the 3 batches of DDGS was 818, 594, and 308 μm. In addition, the original DDGS sample was analyzed for mycotoxin concentrations at Romer Labs (Union, MO). Aflatoxin B1, B2, G1, and G2 were analyzed by HPLC with fluorescence detection (**HPLC-FLD**) using a Romer derivatization unit (Romer Labs, Inc., Union, MO), zearalenone was quantified by HPLC-FLD using a ZearaStar IAC column (Romer Labs, Inc.), fumonisin B1, B2, and B3 were measured by HPLC-FLD using a MultiSep 211 column (Romer Labs, Inc.), and deoxynivalenol was analyzed by a dual column quantitative TLC method. There were no detectable aflatoxins or fumonisins, but small concentrations of deoxynivalenol (1 mg/kg) and zearalenone (200 μg/kg) were detected.

Experimental Design and Diets

Thirty-six barrows were assigned to 1 of 4 experimental diets according to a completely randomized block design, resulting in 9 replicate BW blocks and 9 pigs per dietary treatment. Experimental diets consisted of a corn basal diet (particle size of 878 μm), and 3 diets containing 30% DDGS with particle size of 818 μm (**coarse**), 594 μm (**medium**), or 308 μm (**fine**).The basal diet was formulated on an available P basis and was designed to meet the NRC (1998) requirements for all minerals and vitamins of 40 kg pigs (Table 1). Corn was replaced with 30% DDGS in each of the 3 particle size diets. Titanium dioxides were added to all experimental diets to serve as an indigestible marker at a level of 0.2% to provide an alternative method for determining energy and nutrient digestibility. The calculated nutrient composition of the basal and DDGS diets were based on the NRC (1998) nutrient composition tables for corn and corn DDGS and were shown in Table 1.

Sample Collection and Analysis

Samples of the corn basal diet and the 3 DDGS diets of different particle sizes were collected and analyzed for poured and drained angle of repose (McGlinchey, 2005) using a modified Hele-Shaw cell (Johnston et al., 2009).

Feed and ingredient samples were collected from each experimental diet and stored at –18°C until subsequent analysis. After the 9-d adaptation period, feces and urine from each pig were collected for a 4-d period. During the collection period, fecal samples were collected 2 times (at 0700 and 1900 h) per day and stored at –18°C.

Table 1. Diet composition and calculated nutrient analysis (as-fed basis)

Item	Diets[1] Corn	DDGS
Ingredient		
Corn	96.80	66.80
DDGS	0.00	30.00
Dicalcium phosphate	1.20	1.20
Limestone	0.90	0.90
Sodium chloride	0.40	0.40
Vitamin–trace mineral premix[2]	0.50	0.50
TiO_2	0.20	0.20
Total	100.00	100.00
Calculated analysis[3]		
ME, kcal/kg	3,310	3,131
CP, %	8.03	13.85
Total P, %	0.49	0.64
Available P, %	0.26	0.43
Ca, %	0.62	0.67
Total Lys, %	0.25	0.36
SID[4] Lys, %	0.19	0.24

[1]Corn = basal control diet and distillers dried grains with solubles (DDGS) = diets containing coarse, medium, and fine particle size DDGS.

[2]Vitamin and mineral premix provided per kilogram of diet: vitamin A, 7,716 IU; vitamin D_3, 1,929 IU; vitamin E, 39 IU; vitamin B_{12}, 0.04 mg; riboflavin, 12 mg; niacin, 58 mg; pantothenic acid, 31 mg; Cu (oxide), 35 mg; Fe (sulfate), 350 mg; I (CaI), 4 mg; Mn (oxide) 120 mg; Zn (oxide), 300 mg; Se (Na_2SeO_3), 0.3 mg.

[3]Calculated analysis was based on the NRC (1998) values for all the ingredients.

[4]SID = standardized ileal digestible.

Fecal samples from each pig were pooled, weighed, and dried in a forced-draft oven at 55 to 60°C. After drying and grinding, subsamples were obtained from the total collected sample and were prepared for further chemical analysis. Total urine output was collected at the same time as the fecal collection in plastic containers located under funnels of the metabolism cages. Thirty milliliters of 6 *M* HCl were added to the urine collection containers to limit microbial growth and reduce loss of ammonia. Urine volume was recorded twice daily and a subsample of approximately 20% of the urine excreted from each pig was collected and stored in a freezer at approximately –18°C. At the end of the collection period, urine samples were pooled for each pig and a subsample was used for further analysis. Urine samples were freeze-dried for energy determination.

Gross energy contents of corn, DDGS, experimental diets, feces, and urine were determined by bomb calorimeter (Parr 1218; Parr Instrument Company, Moline, IL). From these data, the DE and ME content of the 4 diets were calculated by subtracting the GE excreted in feces and urine from GE intake. The DE and ME content of the corn basal diet was then divided by 0.968 (decimal equivalent of the percentage of corn in the basal diet) to calculate the DE and ME content in corn. By subtracting the energy contribution of corn to the DDGS diets from the energy that was measured in each of these diets, the concentrations of DE and ME in DDGS with different particle sizes were calculated by using the difference procedure (Adeola, 2001). The DE and ME content of corn and DDGS of the 3 particle sizes on an as-fed basis was converted to a DM basis using DM values for corn, coarse, medium and fine DDGS (85.7, 93.3, 93.6, and 92.6%, respectively). Nitrogen contents of corn, DDGS, feeds, feces, and urine were determined by the LECO (FP-428; LECO Corporation, St. Joseph, MO) combustion method. Phosphorus concentration in corn, DDGS, feedstuffs, feces, and urine was determined using inductively coupled plasma procedures to calculate diet P digestibility (method 985.01; AOAC Int., 2007). The ATTD (%) of energy, N, and P in each diet was calculated using the following equation: ATTD = [(Nt – Nf)/Nt] × 100%, in which Nt is the total consumption of energy (kcal), N (g), or P (g) from d 10 to 13 and Nf is the total fecal excretion of energy (kcal), N (g), or P (g) originating from the feed fed from d 10 to 13.

Statistical Analysis

Data were analyzed using the Mixed Procedures (SAS Inst. Inc., Cary, NC) with individual pig as the experimental unit. The UNIVARIATE procedure of SAS was used to test homogeneity of the residual from the fitted model. The residual vs. the predicted value plot was used to check normality and outliers of the data set. All data had a normal distribution, constant variance, and no outliers. Analysis of variance was conducted to compare the differences of ATTD of DM, GE, N, and P as well as DE and ME within 3 DDGS diets, using particle size as a fixed effect and BW block as a random effect. Preplanned comparisons of the corn diet vs. 3 DDGS diets were also conducted using ANOVA. The same approach was used to compare the differences of drained and poured angles of repose within the 3 DDGS diets and between the corn diet and all DDGS diets. All results were reported as least square means. Multiple comparisons among treatments were performed using the Tukey adjustment option of SAS. Differences among treatments were considered significant when the *P*-value was less than 0.05, and trends were identified when *P*-values were less than 0.10 but larger than 0.05. In addition, ME data (DM basis) were further analyzed using regression analysis to develop a prediction equation for the effect of DDGS particle size on ME content.

RESULTS

The GE of corn and DDGS was 4,375 and 4,837 kcal/kg on an as-fed basis, respectively, and the CP concentration was 8.81 and 26.93%, respectively (Table 2). The P concen-

Table 2. Analyzed nutrient composition of the experimental diets, corn, and distillers dried grains with solubles (DDGS; as-fed basis)

	Diets[1]				Ingredients	
Item	Corn	Coarse	Medium	Fine	Corn	DDGS
DM, %	87.22	89.12	89.27	88.98	87.10	89.20
CP, %	8.73	13.63	13.70	13.64	8.81	26.93
P, %	0.49	0.60	0.60	0.60	0.23	0.69
GE, kcal/kg	4,148	4,412	4,444	4,430	4,375	4,837

[1]Corn = basal control diet; Coarse = diet containing 30% DDGS with particle size of 818 µm; Medium = diet containing 30% DDGS with particle size of 594 µm; Fine = diet containing 30% DDGS with particle size of 308 µm.

tration of corn and DDGS was 0.23 and 0.69%, respectively.

The corn basal diet had greater ($P < 0.01$) ATTD of DM and GE and tended to have a greater ($P = 0.10$) ATTD of N compared with DDGS containing diets (Table 3). However, ATTD of P was greater ($P < 0.01$) in DDGS containing diets than in the corn diet. Dry matter and GE digestibility were improved by fine grinding DDGS compared with the coarse DDGS diet ($P < 0.05$), but no difference in P and N digestibility was found between fine and coarse DDGS diets.

Gross energy intake and fecal and urine excretion were greater ($P < 0.05$) for DDGS diets compared with the corn basal diet (Table 4). Gross energy intake and urine excretion were not different among DDGS diets, but fecal GE excretion was greater ($P < 0.05$) in the coarse diet compared with the medium and fine DDGS diets whereas fecal GE excretion was not different between the medium and fine DDGS diets (Table 4). Diets containing DDGS had similar DE and ME content compared with corn.

Nitrogen intake and fecal and urine excretion was greater ($P < 0.01$) in DDGS diets compared with the corn basal diet (Table 4). As a result, more N was absorbed and retained ($P < 0.01$) for pigs fed the DDGS diets compared

Table 3. Apparent total tract digestibility of DM, GE, N, and P of diets

	Diets[1]				DDGS		Corn vs. DDGS	
Item	Corn	Coarse	Medium	Fine	SEM	P-value[2]	SEM	P-value[3]
DM, %	90.68	82.81[a]	83.88[ab]	84.32[b]	0.05	0.05	0.38	<0.01
GE, %	88.78	80.81[a]	81.92[ab]	82.65[b]	0.53	0.02	0.45	<0.01
N, %	82.30	80.78	80.69	81.40	0.66	0.36	0.63	0.10
P, %	53.89	58.71	59.16	61.00	1.18	0.36	0.88	<0.01

[a,b]Means within DDGS containing diets with different superscripts are different ($P < 0.05$).

[1]Corn = basal control diet; Coarse = diet containing 30% distillers dried grains with solubles (DDGS) with particle size of 818 µm; Medium = diet containing 30% DDGS with particle size of 594 µm; Fine = diet containing 30% DDGS with particle size of 308 µm.

[2]Comparison among 3 DDGS containing diets.

[3]Comparison between the corn diet and all DDGS containing diets.

with the corn diet (Table 4), but the percentage of N retained was not different among the diets. There were no differences among DDGS diets for N intake and fecal and urine excretion, absorption, or retention (Table 4).

Distillers dried grains with solubles had greater ($P < 0.02$) DE and ME content on an as-fed basis and DE on a DM basis and tended ($P = 0.09$) to have greater ME on a DM basis compared with corn (Table 5). On an as-fed basis, the DE and ME content of the fine particle size DDGS (3,709 and 3,577 kcal/kg, respectively) was greater ($P < 0.05$) than the coarse particle size DDGS (3,487 and 3,345 kcal/kg, respectively), with the medium particle size DDGS being intermediate (3,681 and 3,507 kcal/kg, respectively; Table 5). Similar differences were observed among DDGS particle sizes when DE and ME were expressed on a DM basis. Regression analysis was used to determine the relationship between DDGS particle size (818, 595, and 308 µm) and its ME (kcal/kg) value (DM basis). The resulting regression equation was ME = –0.5401 particle size of

Table 4. Daily energy and N balance of diets (as-fed basis)

	Diets[1]				DDGS		Corn vs. DDGS	
Item	Corn	Coarse	Medium	Fine	SEM	P-value[2]	SEM	P-value[3]
GE intake, kcal	4,320	4,766[a]	4,747[ab]	4,734[b]	118.30	0.71	114.23	<0.01
GE in feces, kcal	485	912	854	817	18.74	<0.01	19.04	<0.01
GE in urine, kcal	110	126	136	122	9.15	0.37	7.85	0.03
DE, kcal/kg	3,212	3,192[a]	3,250[b]	3,258[b]	20.83	0.02	17.56	0.40
ME, kcal/kg	3,120	3,088[a]	3,136[ab]	3,157[b]	21.84	0.05	17.32	0.78
N intake, g	14.58	23.44	23.39	23.40	0.58	0.96	0.53	<0.01
N in feces, g	2.60	4.49	4.49	4.36	0.09	0.37	0.09	<0.01
N in urine, g	5.17	8.32	8.37	8.22	0.29	0.81	0.31	<0.01
N absorbed, g	11.99	18.95	18.90	19.04	0.59	0.81	0.52	<0.01
N retained, g	6.82	10.63	10.53	10.82	0.37	0.59	0.33	<0.01
N retention, %	47.06	45.25	44.89	46.89	0.66	0.32	1.35	0.42

[a,b]Means within DDGS containing diets with different superscripts are different ($P < 0.05$).

[1]Corn = basal control diet; Coarse = diet containing 30% distillers dried grains with solubles (DDGS) with particle size of 818 µm; Medium = diet containing 30% DDGS with particle size of 594 µm; Fine = diet containing 30% DDGS with particle size of 308 µm.

[2]Comparison among 3 DDGS containing diets.

[3]Comparison between the corn diet and all DDGS containing diets.

Table 5. Digestible energy, ME, and N retention rate of corn and coarse, medium, and fine particle size distillers dried grains with solubles (DDGS)[1]

		DDGS					Corn vs. DDGS	
Item	Corn	Coarse	Medium	Fine	SEM	*P*-value[2]	SEM	*P*-value[3]
DE, kcal/kg (as fed)	3,212	3,487[a]	3,681[ab]	3,709[b]	69.45	0.02	54.30	<0.01
DE, kcal/kg DM	3,682	3,738[a]	3,932[b]	4,006[b]	77.91	0.02	61.13	0.02
ME, kcal/kg (as fed)	3,120	3,345[a]	3,507[ab]	3,577[b]	72.81	0.05	55.01	<0.01
ME, kcal/kg DM	3,577	3,583[a]	3,745[ab]	3,862[b]	81.65	0.04	62.09	0.09
N retention, %	47.06	46.05	44.84	49.50	2.21	0.32	2.00	0.92

[a,b]Means within DDGS with different superscripts differ ($P < 0.05$).

[1]Corn = corn with a mean particle size of 878 μm; Coarse = diet containing 30% distillers dried grains with solubles (DDGS) with particle size of 818 μm; Medium = diet containing 30% DDGS with particle size of 594 μm; Fine = diet containing 30% DDGS with particle size of 308 μm.

[2]Comparison among 3 DDGS.

[3]Comparison between the corn and all DDGS.

DDGS + 4039.7 (r = 0.44; $P = 0.02$). No difference was observed for N retained between corn and DDGS or among different DDGS particle sizes (Table 5).

Phosphorus intake and fecal excretion and retention were greater ($P < 0.05$) in DDGS diets compared with the corn diet (Table 6). There were no differences among DDGS diets for P intake and fecal and urine excretion or retention (Table 6).

Diet flowability, as measured by the increased drained angle of repose (Figure 1), was reduced ($P < 0.01$) in the 30% DDGS diets compared with the corn diet, and flowability was the least ($P < 0.01$) for the fine particle size DDGS diet compared with the medium and coarse DDGS diets. However, using poured angle of repose as a measure of flowability (Figure 1), there were no differences between the corn diet and the DDGS diets, nor were there differences among diets with different DDGS particle sizes.

DISCUSSION

The current study determined the effects of DDGS particle size on nutrient digestibility, DE and ME content, and flowability in diets for growing pigs. To determine nutrient digestibility, feces and urine from each pig were collected for 4-d after a 9-d adaptation period. For digestibility trials, feces may be collected using a "time-based" approach, as used in the current study as well as previous studies (Lammers et al., 2008; Anderson et al., 2012) or by using colored markers that are added to feed to mark the beginning and end of fecal collection (Adedokun and Adeola, 2005; Pedersen et al., 2007). With the "marker-to-marker" method, it is assumed that the marker moves at the same rate as the digesta in the lumen of the gastrointestinal tract and does not diffuse into adjacent unmarked digesta and that pigs have no aversion to feed containing a marker. Furthermore, the time of marker appearance and disappearance in feces can be somewhat subjective. Therefore, we chose to use the time-based approach for fecal collection reasoning that it is an acceptable method if constant daily feed intake over an extended adaptation period (9 d in the current

Table 6. Daily P balance of diets (as-fed basis)[1]

		DDGS					Corn vs. DDGS	
Item	Corn	Coarse	Medium	Fine	SEM	*P*-value[2]	SEM	*P*-value[3]
P intake, g	5.1	6.5	6.4	6.4	0.16	0.18	0.15	<0.01
P in feces, g	2.4	2.7	2.6	2.5	0.11	0.22	0.09	0.02
P in urine, g	1.1	1.2	1.4	1.3	0.11	0.53	0.09	0.07
P retained, g	1.7	2.6	2.4	2.6	0.11	0.39	0.09	<0.01
P retention, %	32.7	39.9	37.5	40.5	1.72	0.43	1.49	<0.01

[1]Corn = basal control diet; Coarse = diet containing 30% distillers dried grains with solubles (DDGS) with particle size of 818 μm; Medium = diet containing 30% DDGS with particle size of 594 μm; diet containing Fine = 30% DDGS with particle size of 308 μm.

[2]Comparison among 3 DDGS containing diets.

[3]Comparison between the corn diet and all DDGS containing diets.

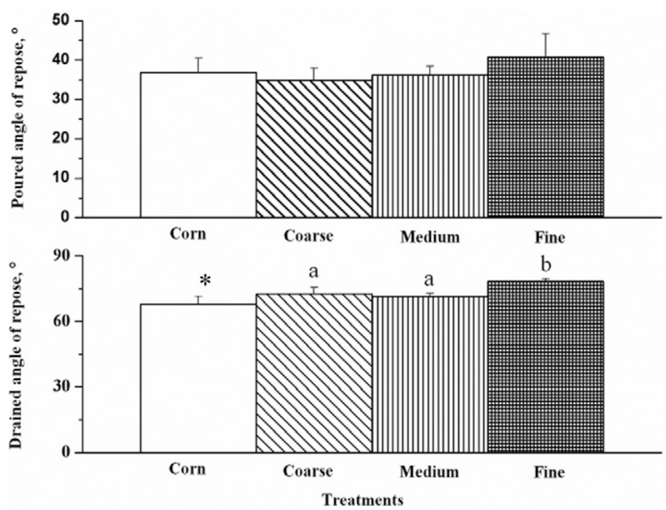

Figure 1. Drained and poured angle of repose of corn basal diet (Corn), 818 μm particle size distillers dried grains with solubles (DDGS) diet (Coarse), 594 μm particle size DDGS diet (Medium), and 308 μm particle size DDGS diet (Fine). Data are presented as least squares means ± SE. [a,b]Means within DDGS containing diets with different superscripts are different ($P < 0.05$). *Drained angle of repose for the corn diet was less than the 3 DDGS containing diets ($P < 0.05$).

study) is achieved and feces is then collected for several days (4 d in the current study).

Nursery pigs are able to use moderate but not high dietary levels of fiber (Weber et al., 2008). The reduced DM digestibility in DDGS diets compared with corn was likely due to the greater NDF content of DDGS compared with corn, which results in an increased amount of feces excreted (Stein and Shurson, 2009). Urriola et al. (2010) reported that the average NDF content among 8 corn DDGS sources was 37.6% (as-fed basis) and ATTD of NDF was 59% but ranges from 52 to 66%. Therefore, pigs are only able to digest about 60% of the NDF in DDGS resulting in increased fecal excretion. However, reducing DDGS diet particle size improved DM digestibility. It is well established that reducing particle size of complete feeds and feed ingredients generally improves nutrient digestibility (Wondra et al., 1995) by increasing the surface area of feed exposed to digestive enzymes. This improvement in nutrient digestibility reduces fecal excretion (manure production). Several researchers have consistently demonstrated improvements in growth rate and feed conversion when feeding diets of low average particle size compared with feeding more coarsely ground diets (Hedde et al., 1985; Giesemann et al., 1990; Healy et al., 1994). These improvements in growth performance are a direct result of improved DM digestibility when particle size of the diet is reduced.

Gross energy intake along with fecal and urine GE excretion was greater for DDGS diets compared with the corn basal diet. These results are consistent with those reported by Stein and Shurson (2009) where the GE of corn was reported to be 4,496 kcal/kg DM compared with an average GE in DDGS of 5,434 kcal/kg DM, but ATTD of energy was greater in corn (90.4%) compared with DDGS (76.8%). Gross energy intake and urine excretion was not different among DDGS diets, but fecal GE excretion was greater in the coarse diet compared with medium and fine diets. These responses in fecal GE excretion are consistent with those observed for the effects of DDGS particle size on DM digestibility and indicate that reducing DDGS particle size has a positive effect on diet DE content. These results also agree with those reported by Mendoza et al. (2010) who showed that DE and ME content of DDGS can be improved by grinding to a finer particle size.

Nitrogen intake and fecal and urine excretion were greater in DDGS diets compared with the corn diet. Nitrogen intake for pigs consuming DDGS diets was greater because DDGS contains approximately 3 times more CP or N than corn, diets were formulated without the use of supplemental AA sources (e.g., soybean meal and synthetic AA), and diets were not balanced for AA. Because the diets contained Lys and other AA below the requirement of the pig and the DDGS diets contained more digestible Lys than the corn diet, more N was absorbed and retained for pigs fed DDGS diets compared with the corn diet. However, the percentage of N retained in pigs fed the corn basal and DDGS diets was not different. Corn and corn co-products (i.e., DDGS) have poor protein quality (low Lys:CP) relative to the requirement of the pig. Therefore, excess N was excreted in feces and urine due to inadequate Lys in the diet (Noblet et al., 1987). There were no differences among DDGS diets for N intake and fecal and urine excretion, absorption, or retention. This indicates that DDGS particle size has no measurable effect on diet N digestibility, retention, or excretion when added at a level of 30% DDGS to a corn basal diet.

Diets containing DDGS had similar DE and ME content compared with the corn basal diet, but DDGS had greater DE and ME content on an as-fed and DM basis compared with corn. On an as-fed basis, the DE and ME content of the fine particle size DDGS (3,709 and 3,577 kcal/kg, respectively) were greater than the coarse particle size DDGS (3,487 and 3,345 kcal/kg, respectively), with the medium particle size DDGS being intermediate (3,681 and 3,507 kcal/kg, respectively). Similar differences were observed among DDGS particle sizes when DE and ME were expressed on a DM basis. Pedersen et al. (2007) reported that DE and ME values of DDGS can vary significantly among different sources and ranged from 3,947 to 4,593 kcal of DE/kg of DM and 3,674 to 4,336 kcal of ME/kg of DM. The DE and ME values we obtained for DDGS were less than those reported by Pedersen et al. (2007) but comparable with those reported by Stein et al. (2006). Furthermore, our ME values were similar (3,583 to 3,862 kcal/kg DM) to the range (3,575 to 3,976 kcal/kg) in ME values from 4 DDGS sources reported by Stein et al. (2009). Several studies have been reported to show that nutrient content (Spiehs et al., 2002), fiber content (Urriola et al., 2010), and AA content (Urriola et al., 2009) varies among DDGS sources. As a result, it would be expected that the DE and ME content would also vary among sources. The DDGS source used in the current study contained 7.85% ether extract, which is less than the ether extract content (8.6 to 12.4%) of DDGS sources evaluated by Pedersen et al. (2007). Therefore, the reduced fat content of the DDGS source used in the current study was likely the primary contributing factor to the reduced DE and ME values compared with those reported by Pedersen et al. (2007). However, ether extract content was not measured in DDGS samples evaluated for DE and ME content by Stein et al. (2006), making it difficult to compare the impact of crude fat content on DE and ME values from this study to the current study. The slightly reduced DE and ME values obtained in our study may have also resulted due to the presence of small amounts of mycotoxins (deoxynivalenol and zearalenone) in DDGS source used in our study. However, the primary goal of this study was to estimate the relative changes in DE and ME due to particle size differences in DDGS. Our results suggest that for each 25 μm decrease in particle size from 818 to 308 μm, ME content (kcal/kg) of DDGS (μm) increases by 13.46 kcal/kg on a DM basis [ME = –0.5401 particle size of DDGS + 4039.7 ($r = 0.44$; $P = 0.02$)]. This improvement in ME content is more than twice the improvement in ME content (6.6 kcal/kg) for each 25 μm reduction in corn particle size reported by Gaines and Kocher (2008) over a similar particle size range (450 to 850 μm). This finding is significant because this relationship can be used to account for some of the differences in ME content among DDGS sources when comparing their economic value and energy contribution during diet formulation.

In our study, the corn basal diet was formulated on an available P basis to meet the (NRC, 1998) requirement of a 40 kg growing pig. Because DDGS has a much greater amount of digestible P than corn (Whitney et al., 2001; Pedersen et al., 2007), adding 30% DDGS to the corn basal diet significantly increased total and available P content. Pigs fed diets containing DDGS had greater P intake and increased fecal and urinary P excretion than those fed the corn diet, but the amount of daily P retained and percentage P retention was also increased. These results were in agreement with those reported by Stein and Shurson (2009), which indicated that DDGS was an excellent source of available P for swine. No difference in P retention was observed among diets with different DDGS particle sizes, suggesting that unlike for DE and ME, reducing DDGS particle size has no effect on P digestibility.

In addition to significantly affecting nutrient digestibility (Goodband and Hines, 1988; Wondra et al., 1995), particle size distributions have been widely used as an important indicator to help understand the physical and chemical properties that affect the flowability of particulate materials. Diet flowability, as measured by the increased drained angle of repose, was reduced in the 30% DDGS diets compared with the corn diet, and flowability was the lowest for the fine particle size DDGS diet compared with the medium and coarse DDGS diets. These results indicated that reducing particle size of DDGS results in poorer feed flowability. These results agreed with those reported by Ganesan et al. (2008a,b,c) who indicated that reduced particle size, along with other factors, such as increased moisture and the amount of solubles added to the grains fraction before drying to produce DDGS, contribute to reduced flowability of DDGS. Johnston et al. (2009) also evaluated several physical and chemical characteristics of DDGS and their relationship to flowability. Their results showed that moisture content of DDGS was the main factor affecting flowability of this ingredient and that particle size was not a significant factor. However, the range of DDGS particle size evaluated in that study was from 584 to 668 μm, which was much less than the particle size range of 308 to 818 μm of DDGS when added at a level of 30% to the corn basal diet with a particle size of 878 μm evaluated in this study. In addition to particle size and moisture content, lipid and protein concentrations in DDGS can also play a significant role in affecting its flowability. Ganesan et al. (2009) showed that DDGS samples containing high levels of lipids had a greater flowability problem than DDGS with low lipid concentration. These authors suggested that main reason for the poorer flowability of DDGS sources containing a greater amount of fat may be due to the lipid molecules liquefying at certain temperatures and functioning as glue between particles, making DDGS particles agglomerate, which creates stickiness and caking, thus leading to flowability problems. Because DDGS contains approximately 3 times the amount of lipid compared with corn, it may also partially explain the differences in flowability between the DDGS and corn diets observed in this study. Similar to lipids, a greater concentration of protein could possibly lead to reduced flowability in DDGS as a result of protein–protein or protein–ligand interactions. Bhadra et al. (2009) suggested that a reaction of charged amino acids in DDGS can cause the formation of salt bridges with P or other salts. Prescott and Barnum (2000) reported that flowability of powdered materials is a direct consequence of the synergism among the physical and chemical properties of the material, environmental conditions, such as humidity and temperature changes, time, compaction, pressure distribution throughout the product mass, and other inherent material properties (particle size, roughness and shape) determine flowability of DDGS. Therefore, more systematic analysis of the factors influencing DDGS flowability is necessary overcome these issues (Rosentrater, 2007).

Our results confirm that adding 30% DDGS to a corn based diet reduces flowability and grinding DDGS to 308 and 594 μm further reduces flowability compared with 818 μm particle sizes. However, for each 25 μm decrease in DDGS particle size from 818 to 308 μm, the ME contribution of DDGS to the diet is increased by 13.6 kcal/kg DM. If it is economical and feasible to pellet DDGS diets, the concern about feed flowability may be eliminated and the extra energy value from using finely ground DDGS can be realized. However, if pelleting is not a viable option and diets must be manufactured and fed in meal form, diet flowability may be acceptable if the DDGS particle size is greater than 600 μm and some of the improved ME value of DDGS from a reduced particle size can be obtained. Based on our results, DDGS particle size does not affect N and P digestibility when present in corn based diet at a level of 30%, so there is no additional economic or feeding value due to particle size on these economically important nutrients.

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