CHAPTER 21

Reduced-Oil DDGS in Swine Diets

Introduction

CORN DRIED DISTILLERS GRAINS WITH SOLUBLES (DDGS) has become the most popular, economical and widely available alternative feed ingredient for use in U.S. swine diets in all phases of production. Corn DDGS is used primarily as an energy source in swine diets because it contains approximately the same amount of metabolizable energy (ME) as corn. Therefore, DDGS primarily replaces a portion of the corn when added to swine diets, but it also partially replaces some of the soybean meal and inorganic phosphorus. Numerous studies have shown that DDGS can be included up to 30 percent in starter, grower-finisher, and lactation diets, and up to 50 percent in sow gestation diets, with no detrimental effects on performance. In fact, because of the high diet cost saving potential of DDGS, several swine integrators in the U.S. are evaluating the addition of up to 60 percent reduced-oil DDGS in growing-finishing pig diets. However, to successfully achieve acceptable growth performance and carcass characteristics at these high dietary inclusion rates, accurate energy, digestible amino acids and digestible phosphorus values must be determined specifically for the DDGS source being fed. Fortunately, numerous studies have been conducted to develop equations to predict ME and standardized ileal digestible (SID) amino acid content of reduced-oil DDGS sources to help nutritionists manage variability in precision nutrition swine feeding programs.

Determining Accurate Energy and Digestible Nutrient Values

Metabolizable energy

Widespread adoption of distillers corn oil extraction in the U.S. ethanol industry has resulted in a proportional reduction of the quantity of DDGS produced, and an increase in the variability in ME and nutrient content among sources. Crude fat content in DDGS ranges from 4 to 13 percent, neutral detergent fiber (NDF) content ranges from 21 to 34 percent, and crude protein content ranges from 24 to 35 percent among DDGS sources (Kerr et al., 2013). However, due to the high variability in nutrient content among DDGS sources before oil extraction (Stein and Shurson, 2009), there is not a consistent increase in the concentration of other nutrients among sources after oil is extracted.

Nutrient composition of feed ingredients has a major impact on their energy content, because pigs digest and utilize protein, starch, fiber and lipids with different efficiencies (Patience, 2009). As a result, estimates of the ME content of reduced-oil DDGS for swine have been reported to vary from 2,858 kcal/kg (**Table 1**.) Although these ME estimates vary considerable, they generally indicate that the ME content in corn DDGS is about 93 percent of the ME content relative to corn. However, oil (crude fat) content is a poor single predictor of ME content in DDGS for swine (**Table 2**). The NRC (2012) reported a mean ME content of 3,845 kcal/kg for DDGS sources containing more than 10 percent oil (high oil), 3,801 kcal/kg for sources with 6 to 9 percent oil (medium oil), and 3,476 kcal/kg for sources with less than 4 percent oil (low oil). However, it is important to note that the published ME values for the medium- and low-oil DDGS were based on only a few published values, and therefore, the accuracy of these values is questionable.

Several factors appear to affect variability in ME content of reduced-oil DDGS among sources. Kim et al. (2013) reported that only about 50 percent of the oil in DDGS is digestible for swine, and Kerr et al. (2013) reported that apparent total tract digestibility (ATTD) of ether extract ranges from 53 to 81 percent among sources. Second, ATTD of fiber in DDGS for swine ranges from 23 to 55 percent (Urriola et al., 2010), which also contributes to variable ME content. Differences in EE and fiber digestibility among DDGS sources appear to be due to differences in the porosity of the fiber-starch-protein matrix in various DDGS sources, which affects fermentability of fiber and effectiveness of carbohydrase enzymes (Jha et al., 2015). Particle size varies among DDGS sources, and Liu et al. (2012) showed that ME content of DDGS is improved by grinding to smaller particle size.

dry matter digestibility of the DDGS sources evaluated by Kerr et al. (2013) was relatively high, ranging from 66.8 to 77.3 percent, but there was no strong association between dry matter digestibility and ME content (**Table 3**). However, the range in digestibility was rather large (52.7 to 81.2 percent) among sources but not strongly associated with ME content. Eight of DDGS sources had ether extract digestibility values in the 50th percentile, which partially explains why crude fat content is a single poor predictor of ME content. A significant amount of NDF in DDGS is utilized for energy, with apparent total tract digestibility values ranging from 45.8 to 61.5 percent. These results are similar to those reported by Urriola et al. (2010). Digestibility of nitrogen (crude protein) was less variable among DDGS sources, and ranged from 76.9 to 84.8 percent, but was poorly associated with ME content. Excess nitrogen can

Table 1. Summary of published estimates for ME (kcal/kg dry matter) content of DDGS relative to ME content of corn (NRC, 2012)

		ME of DDGS				DDGS relative to corn[1] (%)
Item	**n**	**Average**	**Least value**	**Greatest value**	**SD**	
Hastad et al., 2004[2]	2	4,047	3,986	4,108	-	105.3
Hastad et al., 2004[3]	2	3,679	3,476	3,882	-	95.7
Stein et al., 2006	4	3,378	-	-	-	87.9
Pedersen et al., 2007	10	3,897	3,674	4,336	221	101.4
Stein et al., 2009	4	3,750	3,575	3,976	168	97.6
Dahlen et al., 2011	2	2,962	2,959	2,964	-	77.0
Jacela et al., 2011[4, 5]	1	2,858	-	-	-	74.3
Liu et al., 2012	3	3,730	3,583	3,862	140	97.0
Anderson et al., 2012	6	3,790	3,414	4,141	252	98.6
Anderson et al., 2012[5]	1	3,650	-	-	-	94.9
Kerr et al., 2013[5]	15	3,435	3,266	3,696	140	89.3
NRC, 2012, >10 % oil	-	3,845	-	-	-	100.0
NRC, 2012, > 6 and < 9 % oil	-	3,801	-	-	-	98.9
NRC, 2012, < 4 % oil	-	3,476	-	-	-	90.4
Graham et al., 2014a[4, 5]	1	3,365	-	-	-	87.5
Graham et al., 2014b[5]	4	3,744	3,481	3,905	183	97.4
Adeola et al., 2014	1	3,559	-	-	-	92.6

[1] Average ME of DDGS sources as percentage of ME value of corn from NRC (2012)

[2] ME of DDGS determined using metabolism study. Moisture content was not reported, and values were presented on dry matter basis assuming 89.3 percent dry matter (NRC, 2012)

[3] ME of DDGS determined using growth assay. Moisture content was not reported, and values were presented on dry matter basis assuming 89.3 percent dry matter (NRC, 2012)

[4] ME was calculated using equation from Noblet and Perez (1993) based on determined DE and analyzed chemical composition

[5] Studies involved reduced-oil (less than 10 percent) DDGS sources

Table 2. Ranking of ME content of DDGS sources with variable crude fat content and other nutrient components for swine (dry matter basis; adapted from Kerr et al., 2013)

DDGS Source	ME, kcal/kg	ME/GE %	Crude fat %	NDF %	Crude protein %	Starch %	Ash %
15	3,696	72.8	10.9	31.6	29.0	3.3	5.4
13	3,604	74.6	5.6	31.6	30.6	3.3	6.1
8	3,603	69.7	13.2	34.0	30.6	1.3	5.3
11	3,553	69.3	11.8	38.9	32.1	1.1	4.9
9	3,550	71.6	9.7	28.8	29.8	2.8	5.0
6	3,513	70.8	9.6	33.0	30.1	3.4	4.9
7	3,423	69.3	10.1	38.2	30.3	2.2	5.0
2	3,400	67.0	11.1	36.5	29.7	3.9	4.3
4	3,362	68.7	8.6	35.7	32.9	0.8	5.1
3	3,360	66.4	10.8	38.6	29.7	1.6	4.6
10	3,327	67.2	10.0	35.9	32.7	1.0	5.3
1	3,302	65.0	11.2	44.0	27.7	1.8	4.4
12	3,286	68.8	4.9	30.5	31.2	3.3	5.8
5	3,277	65.0	11.1	39.7	31.6	0.9	5.0
14	3,266	66.2	7.5	33.9	30.8	2.5	5.7

Table 3. Ranking of ME content of DDGS sources with variable crude fat content and other nutrient components for swine (dry matter basis; adapted from Kerr et al., 2013)

DDGS Source	ME, kcal/kg	ATTD DM %	ATTD Ether extract %	ATTD NDF %	ATTD Nitrogen %	ATTD Carbon %
15	3,696	72.5	81.2	45.8	80.5	74.1
13	3,604	77.3	69.8	57.4	83.4	78.1
8	3,603	71.6	68.5	57.1	81.0	73.0
11	3,553	70.4	65.8	53.3	82.5	72.4
9	3,550	73.8	58.2	55.2	84.8	74.7
6	3,513	74.2	53.3	60.6	82.8	74.3
7	3,423	71.9	52.7	61.5	80.6	73.2
2	3,400	70.5	57.2	57.4	79.7	71.0
4	3,362	73.3	67.1	51.8	77.0	72.3
3	3,360	69.6	54.7	58.2	81.8	70.2
10	3,327	70.4	57.6	57.2	81.8	70.5
1	3,302	66.8	54.8	56.3	76.9	67.9
12	3,286	72.4	65.7	49.8	82.6	73.6
5	3,277	67.4	59.4	54.2	82.1	68.3
14	3,266	67.7	72.7	44.5	78.0	69.0

be utilized as energy, but it is an energetically expensive process. Similarly, carbon digestibility was relatively high and ranged from 67.9 to 78.1 percent, with no clear association with ME content. Therefore, the ME content of DDGS with variable oil content is determined by a combination of digestible energy contributing fractions (NDF, ether extract, and crude protein) and not solely a function of ether extract content or digestibility.

Accurate and precise estimation of ME values for DDGS sources is important for accurate diet formulation and optimizing the nutritional and economic value of DDGS in swine diets. Several studies have been conducted to develop digestible energy (DE) and ME prediction equations based on physical and chemical composition of corn DDGS sources for swine (Stein et al., 2006; Pedersen et al., 2007; Stein et al., 2009; Anderson et al., 2012; Kerr et al., 2013) and to manage variability in ME content among sources. These equations have been cross-validated for swine (Urriola et al., 2014). The most precise (prediction error = 144 kcal/kg) and accurate (bias = 19 kcal/kg) DE equation was:

DE = -2,161 + (1.39 × gross energy) – (20.7 × NDF) – (49.3 × EE)

The most precise (prediction error = 149 kcal/kg) and accurate (bias = -82 kcal/kg) ME equation uses the DE value obtained from the previous equation as follows:

ME = -261 + (1.05 × DE) – (7.89 × crude protein) + (2.47 × NDF) – (4.99 × EE)

To further evaluate the most precise and accurate DE and ME prediction equations identified by Urriola et al. (2014), Wu et al. (2016a) conducted a growing-finishing experiment to compare the effects of adding 40 percent DDGS from three sources containing 6 percent (LOW), 10 percent (MED) and 14 percent (HIGH) EE, but similar predicted ME (3,258, 3,315 and 3,232 kcal/kg as-fed, respectively), compared with corn-soybean meal (CON) diets, on growth performance, carcass composition and pork fat quality (**Table 4**). Diets contained similar concentrations of standardized ileal digestible amino acids and standardized total tract digestible phosphorus within each phase. Results from this study showed that pigs fed diets containing 40 percent DDGS are likely to have slightly depressed feed intake, which may be due to the elevated fiber content in DDGS compared with that in maize-soybean meal diets. However, feeding DDGS with variable oil content, but similar predicted ME content, had no effect on overall ADG and carcass characteristics. The lower oil content of the low and med DDGS sources reduced polyunsaturated fatty acid intake of pigs, and resulted in improved pork fat quality by reducing iodine value (IV) of belly fat. Furthermore, these results show that the ME content of DDGS with greater than 6 percent oil content can be accurately and precisely predicted using the best equations from Urriola et al. (2014). However, based on slightly reduced gain:feed for pigs fed the low-oil (6 percent EE) DDGS diet,

Table 4. Effects of dietary DDGS with variable ether extract (EE) content on overall growth performance, carcass characteristics, and belly fat quality of growing-finishing pigs (adapted from Wu et al., 2016a)

		40% DDGS			
Item	**CON[1]**	**LOW[1]**	**MED[1]**	**HIGH[1]**	**SEM[2]**
No. Pens	12	12	12	12	
Body weight, kg					
Initial	39.24	39.52	38.95	39.58	0.90
Final	122.7^{a}	118.7^{b}	118.6^{b}	119.4^{b}	0.90
Overall ADFI, kg	2.72^{a}	2.65^{ab}	2.61^{b}	2.60^{b}	0.03
Overall ADG, kg	0.97^{a}	0.92^{b}	0.92^{b}	0.93^{b}	0.01
Overall Gain:Feed	0.368^{a}	0.356^{b}	0.365^{a}	0.367^{a}	0.003
Hot carcass weight, kg	90.97^{a}	86.69^{b}	86.80^{b}	87.24^{b}	0.88
Carcass yield %	74.2^{a}	73.0^{b}	72.9^{b}	73.0^{b}	0.20
Backfat depth[3], mm	20.6	19.9	19.2	19.8	0.5
Loin muscle area[3], cm^2	42.06^{a}	39.38^{b}	39.09^{b}	39.37^{b}	0.53
Fat-free lean[3] %	51.9	51.6	51.9	51.6	0.3
Belly fat IV[4]	60.17^{a}	70.74^{b}	72.03^{b}	76.41^{c}	0.79

[1] CON = corn-soybean meal control diet; LOW = low-oil DDGS (5.9 percent EE) diet; MED = medium-oil DDGS (9.9 percent EE) diet; and HIGH = high-oil DDGS (14.2 percent EE) diet

[2] Pooled SEM

[3] Final BW was used as covariate in the statistical analysis.

[4] IV = iodine value

[a,b] Means with different superscripts within a row differ (P less than 0.05)

further refinements in ME prediction equations may be needed to accurately predicting ME content of low-oil (less than 6 percent EE) DDGS sources. As described by Urriola et al. (2014) it is important to note that energy prediction equations from NRC (2012) should not be used because they underestimate the true ME content of reduced-oil DDGS sources.

Net energy

The net energy (NE) system provides a more accurate method of meeting the energy requirements of pigs fed high-fiber diets than the ME system (Noblet et al., 1994). As a result, swine nutritionists in the U.S. are using the NE system to formulate DDGS diets to achieve satisfactory growth performance and carcass composition at high (greater than 30 percent) diet inclusion rates. Unfortunately, a limited number of studies have been conducted to determine the NE (dry matter basis) content of DDGS sources (**Table 5**).

Using the comparative slaughter method, Gutierrez et al. (2014) determined NE concentrations of a conventional DDGS source (13.0 percent EE) and an uncooked (enzyme-treated prior to fermentation) DDGS source (2.6 percent EE). The conventional DDGS source had less NE content when fed to pigs during the growing phase compared with feeding it during the finishing phase (2,173 vs. 2,697 kcal/kg, respectively). However, the NE content of the uncooked DDGS source was not different between the growing and finishing periods (2,120 and 2,058 kcal/kg). It is unclear why the NE content of the uncooked DDGS source was less compared with the NE content of the conventional DDGS source during the finishing phase, but not during in growing phase. It may be possible that the greater oil content of conventional DDGS resulted in greater fat accretion in the carcass compared with feeding the lower crude fat uncooked DDGS source, which may be more prominent in the finishing phase because finishing pigs deposit much more carcass lipid than growing pigs (Gutierrez et al., 2014). Furthermore, these NE estimates for DDGS sources were lower than the NE value for corn (NRC, 2012), and were also lower than the NRC (2012) NE values (2,669 kcal/kg for DDGS with greater than 10 percent oil and 2,251 kcal/kg for DDGS with less than 4 percent oil). However, it is important to realize that the NE values in NRC (2012) are questionable because they were not directly determined with in vivo experiments, but were calculated using prediction equations developed based on complete feeds.

Kerr et al. (2015a) determined NE content of six corn DDGS sources using the Dual-energy X-ray absorptiometry method (**Table 6**). Although oil concentrations of these DDGS sources varied from 7.0 to 13.3 percent, NE content was not different among sources (2,012 to 2,253 kcal/kg). The average NE content of these six sources was 2,135 kcal/kg, with the low NE value being 29.4 and 12.3 percent less than the NE content of corn (NRC, 2012) and conventional DDGS (average between grower and finisher periods) determined by Gutierrez et al. (2014), respectively. Results from this study confirmed once again that crude fat content of DDGS is not a good indicator of energy content among DDGS sources. Unfortunately, Kerr et al. (2015) were unable to develop NE prediction equations from this limited number of DDGS sources because of a lack of high variability in chemical composition among the sources evaluated.

In other experiments, Graham et al. (2014b) estimated the NE concentrations of four DDGS sources by calculating and comparing the NE efficiencies of pigs fed DDGS diets with pigs fed a corn-soybean meal control diet and using NRC (2012) published values for NE content of corn and soybean meal. Estimated NE values ranged from 2,122 to 2,893 kcal/kg and appeared to be positively correlated to the EE concentration of DDGS (NE, kcal/kg = 1,501.01 + 115.011 × EE %; adjusted $R^2 = 0.86$). Most recently, Wu et al. (2016) fed 4 DDGS sources with variable crude fat and estimated NE content to growing-finishing pigs and used growth performance responses and the NRC (2012) requirement model to estimate actual NE content of these sources. The NE estimates ranged from 2,182 to 2,915 kcal/kg, with an average of 2,660 kcal/kg dry matter. These estimates are substantially greater than those published in NRC (2012), but similar to those reported by Graham et al. (2014b). Wu et al. (2016c) used the results from Kerr et al. (2015a) and Wu et al. (2016c) to develop a NE prediction equation for DDGS with oil content ranging between 5.8 to 12.2 percent ether extract:

NE (kcal/kg dry matter) = -1130.5 + (0.727 × gross energy) + (23.86 × ether extract) – (10.83 × NDF); ($R^2 = 0.99$; phosphorus less than 0.01).

However, the accuracy of the predicted NE values for RO-DDGS using this equation has not been validated in feeding trials with growing-finishing pigs. Summarizing all of the available published results, the most conservative estimate of

Table 5. Summary of published estimates for NE (kcal/kg dry matter) content of corn DDGS

		NE of DDGS				
Item	**n**	**Average**	**Least value**	**Greatest value**	**SD**	**DDGS relative to corn[1] (%)**
Gutierrez et al., 2014[2]	1	2,435	-	-	-	80.5
Gutierrez et al., 2014[3]	1	2,089	-	-	-	69.1
Graham et al., 2014b	4	2,551	2,122	2,893	318.8	84.3
Kerr et al., 2015a	6	2,135	2,012	2,253	89.2	70.6
Wu et al., 2016c	4	2,660	2,182	2,915	-	87.9
NRC, 2012, > 10 % oil	-	2,384	-	-	-	78.8
NRC, 2012, > 6 and < 9 % oil	-	2,343	-	-	-	77.4
NRC, 2012, < 4 % oil	-	2,009	-	-	-	66.4

[1] Average NE of DDGS sources as percentage of NE value of corn from NRC (2012)

[2] Conventional DDGS source

[3] Uncooked (enzyme-treated prior to fermentation) DDGS source

Table 6. Ranking of NE content of DDGS sources with variable crude fat content and other nutrient components for swine (dry matter basis; adapted from Kerr et al., 2015)

DDGS Source	NE, kcal/kg	ME, kcal/kg	NE/GE %	NE/ME %	Crude fat %	NDF %	Crude protein %	Starch %	Ash %
6	2,381	3,734	44.8	59.3	11.4	31.1	32.2	4.7	5.5
5	2,326	3,893	45.9	60.4	7.0	27.8	29.8	4.4	5.5
1	2,262	3,830	42.6	58.2	13.3	38.3	29.7	2.5	4.8
2	2,249	3,723	43.0	58.9	10.4	38.5	32.0	2.3	4.7
3	2,219	3,874	42.6	55.5	9.1	39.6	31.6	3.8	5.4
4	2,129	3,716	42.3	56.7	8.0	31.0	30.6	4.9	5.6

NE content in reduced-oil DDGS is 2,012 kcal/kg, but using an average NE value of 2,374 kcal/kg dry matter may be appropriate for most DDGS sources.

Digestible amino acids

One of the most significant constraints that affect the dietary inclusion rates of DDGS is the inherent variability in digestible amino acid content among sources. Several studies have been conducted and published that have determined the standardized ileal digestibility (SID) of amino acids in various DDGS sources. However, to use higher dietary inclusion rates of DDGS, nutritionists need methods to dynamically estimate digestible amino acid content of the specific DDGS source(s) they are using in commercial feed formulas. Currently, dietary DDGS inclusion rates are restricted because of concerns on potential reductions in growth performance when feeding high DDGS diets resulting from less digestible and less balanced amino acid profile of DDGS compared with soybean meal, as well as variability among sources.

Olukosi and Adebiyi (2013) summarized amino acid composition data of corn DDGS sources from published studies from 1997 to 2010 (**Table 7**). Although the majority of these DDGS sources contained greater than 10 percent crude fat, these data are useful in understanding the inherent variability in total amino acid content among DDGS sources. Furthermore, these researchers showed that the correlations between crude protein content and arginine (r = 0.44), isoleucine (r = 0.26), lysine (r = 0.22) and tryptophan (r = 0.33) were low and not significant. This means that crude protein is a poor indicator of the concentrations of these amino acids in corn DDGS and prediction equations were not developed. Although the concentrations of other indispensable amino acids were significantly correlated with crude protein content (r = 0.68, 0.49, 0.73, 0.81, 0.59 and 0.61 for histidine, leucine, methionine, phenylalanine, threonine and valine, respectively), they were generally low and resulted in prediction equations with low R^2 values (0.23 to 0.66). These results confirm that crude protein content is a poor predictor of amino acid content in corn DDGS, and direct measurement of amino acids is required for accurate determinations.

Four studies have been conducted to determine the effects of partial oil extraction from DDGS on standardized ileal digestibility (SID) of amino acids and SID amino acid content (SIDC). Ren et al. (2011) showed that SID of amino acids in low-oil (2.9 to 4.1 percent ether extract) DDGS sources were not different than conventional high-oil (greater than 10 percent ether extract). Li et al. (2015) evaluated different condensed distillers solubles ratios and oil content in DDGS and showed that reduced-oil DDGS had lower SID of amino acids than high-oil DDGS, and a high CDS ratio tended to decrease SID of amino acids in high-oil DDGS, but not in low-oil DDGS. Curry et al. (2014) showed that 2 sources of reduced-oil DDGS (8.4 and 7.9 percent acid hydrolyzed EE; dry matter basis) had decreased SID values for most amino acids relative to conventional DDGS (12.7 percent acid hydrolyzed EE), and that the lower amino acid digestibility in reduced-oil DDGS could not be overcome by adding fat to the diets (**Table 8**). A study conducted by Gutierrez et al. (2016) also found that apparent ileal digestibility of dietary lysine was decreased when increasing amounts of a reduced-oil DDGS source was added to corn-soybean meal based swine diets. However, addition of 6 percent soybean oil to these diets increased the apparent ileal digestibility of lysine. It may be possible that significant changes occur in the fiber-starch-protein matrix during the oil extraction process, causing greater susceptibility to heat damage during the drying process, which may contribute to the slight reductions in amino acid digestibility, observed in these two studies. Prediction equations have been

Table 7. Variation in indispensable amino acid composition of corn DDGS sources from 1997 to 2010 (adapted from Olukosi and Adebiyi, 2013)

	Average	Minimum	Maximum	SD	CV %
Arginine %	1.22	1.06	1.46	0.098	8.0
Cysteine %	1.73	1.49	1.97	0.057	11.1
Histidine %	0.74	0.65	0.91	0.070	9.4
Isoleucine %	1.07	0.96	1.25	0.072	6.7
Leucine %	3.21	2.89	3.62	0.210	6.6
Lysine %	0.90	0.62	1.11	0.118	13.1
Methionine %	0.52	0.44	0.72	0.063	12.0
Phenylalanine %	1.29	1.09	1.51	0.123	9.6
Threonine %	1.03	0.93	1.16	0.067	6.5
Tryptophan %	0.22	0.16	0.26	0.022	10.3
Valine %	1.42	1.30	1.61	0.095	6.7

Table 8. Total amino acid content, standardized ileal digestibility (SID), and standardized ileal digestible amino acid content (AIDC) of DDGS sources with varying crude fat content for swine (as-fed basis; adapted from Curry et al., 2014).

	11.5% oil DDGS			7.5% oil DDGS			6.9% oil DDGS		
	Total %	**SID %**	**SIDC %**	**Total %**	**SID %**	**SIDC %**	**Total %**	**SID %**	**SIDC %**
Dry matter %	90.6	-	-	89.0	-	-	87.5	-	-
AH EE[1] %	11.5	-	-	7.5			6.9		
Crude protein %	25.7	79.8^{a}	20.5	28.0	72.8^{b}	20.4	27.9	73.6^{b}	20.5
Arg	1.22	87.7^{a}	1.07	1.22	81.0^{c}	0.99	1.24	82.5^{bc}	1.02
Cys	0.62	76.0^{a}	0.47	0.62	67.8^{c}	0.42	0.63	68.8^{bc}	0.43
His	0.69	80.9^{a}	0.56	0.75	73.5^{b}	0.55	0.71	74.6^{b}	0.53
Ile	1.03	79.8^{a}	0.82	1.12	72.9^{b}	0.82	1.06	73.1^{bc}	0.77
Leu	2.79	87.7^{a}	2.45	3.17	83.4^{bc}	2.64	3.07	82.2^{c}	2.52
Lys	0.91	67.9^{a}	0.62	0.91	56.4^{c}	0.51	0.88	61.7^{b}	0.54
Met	0.52	88.1^{a}	0.46	0.59	84.8^{bc}	0.50	0.55	83.6^{c}	0.46
Phe	1.25	84.9^{a}	1.06	1.36	80.3^{bc}	1.09	1.35	79.8^{c}	1.08
Thr	0.97	73.4^{a}	0.71	1.02	66.9^{c}	0.68	1.02	68.2^{bc}	0.70
Trp	0.21	83.1^{a}	0.17	0.20	77.8^{c}	0.16	0.20	81.1^{ab}	0.16
Val	1.30	80.5^{a}	1.05	1.43	74.2^{bc}	1.06	1.33	74.6^{bc}	0.99

^{a,b,c}Means within rows of similar columns with different superscripts are different (P less than 0.05)

[1] AH EE = acid hydrolyzed ether extract

developed for estimating amino acid digestibility in heat-damaged DDGS (Almeida et al., 2013), but they have not been validated for accuracy or precision.

Recently, Zeng et al. (2017) summarized data sets from 22 peer-reviewed publications and one master's thesis published between 2006 and 2015 (**Table 9 and 10**). These data are more reflective of the chemical composition and variability among corn reduced-oil DDGS sources than those reported by Olukosi and Adebiyi (2013). These researchers conducted a meta-analysis to develop standardized ileal digestible amino acid prediction equations for reduced-oil DDGS for swine (**Table 11**). Amino acid and NDF or ADF content of DDGS are good predictors of SID amino acid content of DDGS for growing pigs, and the accuracy and precision of these prediction equations are much improved compared to those from previously published studies. As a result, these equations can be used to accurately estimate the SID amino acid content of a wide range of reduced-oil DDGS sources for swine.

Table 9. Variation in chemical composition of corn DDGS sources fed to swine from 2006 to 2015 (88 percent dry matter basis; adapted from Zeng et al., 2017)

Nutrient	Average	CV %
Crude protein %	27.1	8.7
Crude fiber %	8.2	26.2
NDF %	34.1	13.4
ADF %	11.5	21.2
Ether extract %	8.8	36.3
Ash %	4.1	24.9

Table 10. Variation in total amino acid content and standardized ileal digestibility (SID) and variability (coefficient of variation; CV %) of corn DDGS sources fed to swine from 2006 to 2015 (88 percent dry matter basis; adapted from Zeng et al., 2017)

Indispensible amino acid	Average total %	CV %	SID coefficient %	CV %
Arginine %	1.15	11.8	0.83	6.8
Histidine %	0.74	14.2	0.78	5.5
Isoleucine %	0.99	11.8	0.76	9.2
Leucine %	3.16	13.7	0.85	4.0
Lysine %	0.80	17.9	0.62	13.5
Methionine %	0.54	15.1	0.82	7.0
Phenylalanine %	1.32	12.3	0.82	4.5
Threonine %	1.01	15.5	0.71	7.1
Tryptophan %	0.20	16.3	0.72	12.7
Valine %	1.35	11.1	0.77	5.9

Table 11. Standardized ileal digestible (SID) amino acid content prediction equations for DDGS fed to swine (88 percent dry matter basis; Zeng et al., 2017)

Amino acid, g/kg	Equation	R2
SID Arginine	= -0.26 + (Arg, g/kg × 0.97) – (NDF, g/kg × 0.004)	0.99
SID Histidine	= -0.08 + (His, g/kg × 0.94) – (NDF, g/kg × 0.003)	0.99
SID Isoleucine	= 0.07 + (Ile, g/kg × 0.90) – (NDF, g/kg × 0.005)	0.99
SID Leucine	= 0.30 + (Leu, g/kg × 0.90) – (ADF, g/kg × 0.018)	0.97
SID Lysine	= -1.03 + (Lys, g/kg × 0.88) – (NDF, g/kg × 0.003)	0.98
SID Methionine	= -0.22 + (Met, g/kg × 1.00) – (NDF, g/kg × 0.002)	0.99
SID Methionine + Cysteine	= 0.05 + (Met+Cys, g/kg × 0.92) – (NDF, g/kg × 0.005)	0.99
SID Phenylalanine	= 0.15 + (Phe, g/kg × 0.92) – (NDF, g/kg × 0.004)	0.99
SID Threonine	= 1.30 + (Thr, g/kg × 0.64) – (ADF, g/kg × 0.028)	0.99
SID Tryptophan	= -0.17 + (Trp, g/kg × 0.89)	0.99
SID Valine	= -0.49 + (Val, g/kg × 0.87) – (ADF, g/kg × 0.070)	0.99

Despite the results of initial studies showing that DDGS color (L* and b*) may be useful in estimating digestible amino acid content of DDGS sources for swine and poultry, a recent study conducted by Urriola et al. (2013) showed that color is not an accurate predictor of amino acid digestibility in DDGS. Urriola et al. (2013) determined the standardized ileal digestibility of amino acids in 34 sources of corn DDGS, one source of sorghum DDGS and two sources of wheat DDGS (**Figure 1**). These results show that amino acid digestibility can vary significantly among DDGS sources, and while an L* value less than 50 is better correlated with digestible lysine content than an L* greater than 50, the R^2 in both comparisons is low (0.48 and 0.03, respectively). Therefore, color should not be used as a predictor of digestible amino acid content in corn DDGS.

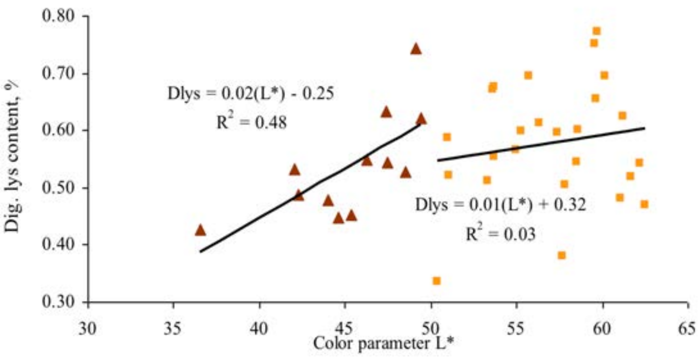

Figure 1. Correlation between lightness of color (L*) and digestible lysine content of 37 sources of DDGS (Urriola et al., 2013)

Researchers at the University of Minnesota have developed methods using optical density and front face fluorescence (Urriola et al., 2013)Lys, Met, Thr and Trp from 34 sources of DDGS to estimate digestibility of amino acids in DDGS. The reduced amino acid digestibility among some sources of DDGS is partly due to heat treatment during the production and drying process. Mild heating of proteins in the presence of reducing sugars forms Schiff's bases or early Maillard products, while more aggressive heating produces advanced Maillard products or melanoidins. A portion of early Maillard products have ring structures, which can be detected using fluorescence. Font face fluoresce is a rapid method that allows quantification of heat damage in DDGS and was calibrated to predict SID of amino acids (Urriola et al., 2013)Lys, Met, Thr, and Trp from 34 sources of DDGS. However, the accuracy of using this method for estimating SID of amino acids among DDGS sources has not been validated.

Studies have also shown that amino acids in DDGS may not only less digestible, but may also be less bioavailable (Fontaine et al., 2007; Pahm et al., 2008). Heat treatment during drying of DDGS can have several effects on the proteins in feed ingredients (Meade et al. 2005). Not only does heat directly degrade lysine, but it also increases the proportion of lysine that is less digestible and less absorbable, or is excreted in urine without utilization after absorption (Rutherfurd, 2015) lysine can undergo Maillard reactions to produce nutritionally unavailable products. The guanidination reaction, the reaction of O-methylisourea with the side chain amino group of lysine that produces homoarginine, has been used to determine the unmodified lysine (reactive lysine). Overall, exposure to heat decreases the proportion of bioavailable lysine that is digestible and utilized for protein deposition, which can lead to reduced growth performance and percentage of carcass lean in pigs (Almeida et al., 2014).

The heat damage to amino acids in DDGS is currently attributed to the Maillard reactions that occur when a mixture of proteins (about 27 percent in DDGS) and sugars or starch (about 2-8 percent in DDGS) are tightly bound during heat treatment (Fontaine et al., 2007). However, lipids (5-12 percent ether extract in DDGS) and products of lipid peroxidation also react with the amino acids in the matrix to produce degradation products that are not bioavailable (Meade et al., 2005). Thermal stress leads to the peroxidation of unsaturated fatty acids (such as linoleic acid in corn oil) which results in the formation of hydroperoxides, aldehydes, ketones and other peroxidation products. Hydroperoxides can oxidize methionine, cystine and tryptophan, while aldehydes and ketones react with lysine and histidine. Previous studies have shown during heat treatment of corn oil when drying DDGS, there is an increase in hydroperoxides and aldehydes, which can be 20 to 25 times greater than found in corn oil from corn grain (Song and Shurson, 2013) growth performance and meat quality. The objective of this study was to determine the lipid peroxidation level in corn DDGS. Therefore, due to the variable oil content among corn DDGS sources, the impact of heat may not only contribute to the formation of Maillard products, but also cause the production of lipid peroxidation products that can reduce the digestibility of lysine and other amino acids.

There are multiple methods that have been developed determine the proportion of bioavailable lysine in feed ingredients including the furosine method (Finot, 2005), the reactive or guanidination method (Rutherfurd, 2015). The guanidination reaction, the reaction of O-methylisourea with the side chain amino group of lysine that produces homoarginine, has been used to determine the unmodified lysine (reactive lysine, and other chemometric methods such as front-face fluorescence (Urriola et al., 2013) Lys, Met, Thr and Trp from 34 sources of DDGS and liquid chromatography-mass spectrometry (LC-MS; Wang et al., 2016). The guanidination and furosine methods are time consuming and expensive. Consequently, these methods have not been further developed for commercial use in estimating amino acid bioavailability in DDGS sources. Front-face fluorescence (FFF) is a rapid analytical method that has promise for use in measuring the portion of bioavailable lysine in DDGS. However, this method has not been validated and only relies on the formation of ring-like structures that fluoresce. A more holistic analytical method may be the use of LC-MS chemometrics that can quantify a multitude of chemical compounds produced during the thermal treatment process. In fact, LC/MS and FFF have been used to determine quality and the consequences of processing milk (Ntakatsane et al., 2011). More research is needed to find practical, fast, accurate and inexpensive methods for estimating bioavailability of amino acids in DDGS for swine and poultry.

Digestible phosphorus

Phosphorus is the third most expensive component of swine diets, and unlike all other grains and grain co-products, DDGS contains a high concentration of total and digestible phosphorus. Therefore, when adding DDGS to swine diets formulated on a digestible phosphorus basis, significant reductions in inorganic supplementation and diet cost can be achieved. In addition, many ethanol plants add phytase during the ethanol and DDGS production process which further improves the phosphorus digestibility of DDGS, but also contributes to variation in digestible phosphorus content among DDGS sources.

Nutritionists are sometimes confused about various ways of expressing the utilization of dietary phosphorus in pigs. Total phosphorus represents all of the phosphorus present in a feed ingredient and includes the indigestible portion of phosphorus known as phytic acid (phytate) in grains and grain co-products. Therefore, if diets are formulated on a total phosphorus basis, overestimation of the digestible phosphorus content may occur because it does not account for the amount that is available for utilization by pigs. Bioavailable phosphorus is the proportion of total phosphorus that is digested, absorbed and available for use in biological functions or stored in the body. Phosphorus bioavailability is usually determined using a slope-ratio assay in digestibility experiments, and theoretically estimates the digestible and post-absorptive utilization of phosphorus at in body tissues. Bioavailablility of phosphorus is also frequently described as available phosphorus. The approach for determining available phosphorus with the slope-ratio assay involves fitting the slope of a linear titration of dietary phosphorus provided by an inorganic phosphorus source and the resulting response (growth rate or bone ash), and comparing it with the linear titrated slope of the same response criteria of the test ingredient. However, this method has the disadvantages of assuming that the bioavailability of the inorganic source is 100 percent, which is not the case, along with differences in estimates based on the response criteria chosen and relatively high cost. Therefore, when using bioavailability estimates for phosphorus, it is important to remember that these estimates are relative to the bioavailability of the reference inorganic source used in the comparison, and that it does not represent true bioavailability. If this is not considered, diets formulated on an available phosphorus basis will overestimate the actual amount of phosphorus being utilized. To overcome these challenges, most recent studies use methodology to estimate apparent total tract digestibility (ATTD) of phosphorus or standardized total tract digestibility (STTD) of P. The difference between ATTD and STTD phosphorus is that STTD corrects for basal endogenous losses of P, resulting in greater accuracy of estimating true digestibility. Therefore, using ATTD phosphorus values will likely underestimate the true digestibility of phosphorus because it does not account for basal endogenous losses. Shen et al. (2002) estimated that basal endogenous losses of phosphorus in corn accounts for about 26 percent of the daily phosphorus requirement for pigs. Therefore, after correcting for endogenous losses, STTD phosphorus values are additive for all feed ingredients and provides the most accurate estimate of the true digestibility of phosphorus in the diet (Gonçalves et al., 2017).

The NRC (2012) list the ATTD and STTD of phosphorus in DDGS containing between 6 to 9 percent oil to be 60 and 65 percent, respectively. Recent studies show that these estimates are low and rather conservative. Almeida and Stein (2010) determined the STTD phosphorus content of DDGS to be 72.9 percent, and the addition of 500 phytase units/kg of diet of a microbial phytase did not improve STTD phosphorus (75.5 percent) unlike the addition of phytase to corn or soybean meal diets. Furthermore, they showed that formulating diets on a STTD phosphorus basis does not reduce pig growth performance, and the use of phytase, DDGS or the combination of both in corn-soybean meal diets reduces phosphorus excretion in growing pigs. In a subsequent study, Almeida and Stein (2012) showed that the addition of 130, 430, 770 or 1,100 FTU/kg of microbial phytase tended to improve STTD of phosphorus 76.9, 82.9, 82.5 and 83.0 percent, respectively. These researchers developed regression equations to predict STTD of phosphorus in DDGS but the R^2 value was only 0.20, and as a result, were not adequate for predicting STTD of phosphorus in DDGS.

Hanson et al. (2011) demonstrated the advantages of formulating DDGS diets on an available phosphorus basis compared with a total phosphorus basis in diets containing 0, 10 or 20 percent DDGS. Results from this study showed that increasing diet inclusion rates of DDGS reduced total dietary phosphorus content and fecal phosphorus concentration, but did not affect phosphorus excretion, retention, or digestibility. Baker et al. (2013) conducted two experiments to compare values of STTD and relative bioavailability of phosphorus (relative to dicalcium phosphate) in DDGS fed to growing pigs. The STTD of phosphorus in dicalcium phosphate and DDGS were 86.1 percent and 58.8 percent, respectively, and the bioavailability of phosphorus in DDGS was 87 percent relative to dicalcium phosphate. However, these researchers concluded that the relative phosphorus bioavailability in DDGS overestimates the true utilization of phosphorus from DDGS, and estimates for STTD of phosphorus cannot be accurately calculated for relative bioavailability phosphorus values in DDGS. Therefore, it is necessary to determine and use STTD values for phosphorus in feed ingredients fed to pigs to achieve optimal phosphorus nutrition.

Rojas et al. (2013) determined STTD of phosphorus in DDGS with (82.8 percent) and without (76.5 percent) microbial phytase added at 870 FTU/kg of diet, and these values were not significantly different. Presumably, the lack of minimal, if any, improvement in STTD phosphorus in these studies resulting from the addition of phytase was due to the relatively low phytate content in the DDGS sources evaluated.

She et al. (2015) determined the STTD of phosphorus in DDGS sources containing 10.3 percent (high-oil), 9.1 percent (medium-oil) and 3.5 percent (low-oil) DDGS sources when 600 FTU/kg of phytase was added to the diets. The STTD of phosphorus in their experiment were 71.2, 70.8 and 71.8 percent for high-, medium-, and low-oil DDGS sources respectively. These data suggest that oil content of DDGS had no effect on STTD of phosphorus in DDGS.

In summary, the greatest accuracy in achieving optimal phosphorus nutrition when feeding DDGS diets to swine is to formulate diets on a STTD phosphorus basis. Results from recent studies have shown that STTD of phosphorus may vary from 59 to 77 percent, but are generally greater than the value of 65 percent reported by NRC (2012). Unfortunately, adequate prediction equations for estimating STTD of phosphorus in DDGS have not been developed for swine. Therefore, use of a conservative estimate of STTD of phosphorus from NRC

(2012) should be used for DDGS from any source in practical diet formulations. The addition of phytase to DDGS diets has minimal effects on improving phosphorus digestibility, which is likely due to the relatively low phytate content in several DDGS sources. Although the relative bioavailability of phosphorus in DDGS has been estimated to be 87 percent relative to dicalcium phosphate, this value overestimates the true utilization of phosphorus from DDGS.

Growth Performance

Numerous studies have been conducted to evaluate the addition of high-oil and reduced-oil DDGS sources at diet inclusion rates up to 60 percent of the diet, using ME or NE formulation methods for nursery and growing finishing pigs. A meta-analysis was conducted to summarized the overall effects of these factors using 26 peer-reviewed references and one thesis published from 2010 to 2017 including: Asmus et al, 2014a; Benz et al., 2011; Coble et al., 2017; Cromwell et al., 2011; Davis et al., 2015; Duttlinger et al., 2012; Graham et al., 2014a,b,c; Hardry matteran, 2013; Jacela et al., 2011; Jha et al., 2013; Jones et al., 2010; Kerr et al., 2015a; Lammers et al., 2015; Lee et al., 2013; Li et al., 2012; McDonnell et al., 2011; Nemechek et al., 2015; Overholt et al., 2016a; Pompeu et al., 2013; Salyer et al., 2013; Seabolt et al., 2010; Tsai et al., 2017; Wang et al., 2012; Wu et al., 2016a; Ying et al., 2013. **Table 12** is a summary of the overall growth performance responses from feeding DDGS diets to nursery and growing-finishing pigs (expressed as a percentage compared with feeding control diets) based on data from these 27 studies and representing 106 observations. There was a small, significant (P less than .05) percentage reduction in ADG (-2.4 percent) and gain:feed (-1.2 percent) of pigs fed DDGS diets compared to those fed control diets with no DDGS, and a trend (P less than 0.10) for a slight reduction (-0.7 percent) in ADFI. However, proper interpretation of these results is extremely important. First, these results are based on studies where more than 20 percent DDGS diets were fed and some studies included in this summary fed diets containing up to 60 percent DDGS. Second, although these overall responses were negative, a 2.4 percent change in ADG is equivalent to growing-finishing pigs gaining 0.90 vs. 0.92 kg per day and having gain:feed of 0.45 vs. 0.46. These small differences are very difficult to measure in commercial swine production systems. Furthermore, the feed cost savings commonly achieved by adding DDGS to swine diets, especially at high (greater than 20 percent) diet inclusion rates far exceeds any slight reduction in growth rate that may occur. Third, these slight reductions were generally due to nutritionists often using inaccurate ME, NE, and digestible amino acid values when formulating DDGS diets, especially in the study representing the poorest (minimum) responses. In fact, the majority of the 106 observations of growth performance responses in the studies showed no change in ADG (72 percent of observations), ADFI (63 percent of obsevations), and gain:feed (67 percent of observations) showed no change when feeding DDGS diets compared with control diets (**Table 13**).

Table 12. Effects of corn DDGS dietary inclusion on growth performance of pigs (summary of 27 studies since 2010)

	DDGS – control (expressed as %)[1]					
	ADG	**ADFI**	**Gain:Feed**	**Initial BW[2], kg**	**Final BW, kg**	**Feeding days**
Observations	106	106	106	106	106	106
Studies	27	27	27	27	27	27
Mean	-2.4**	-0.7*	-1.2**	41.5	101.6	66.4
Minimum	-12.3	-12.8	-17.7	6.7	17.5	20.0
Maximum	4.1	18.0	6.5	105.7	134.9	120

**Means differ from 0 (*P* less than 0.05)

*Means differ from 0 (P less than 0.10)

[1] The inverse of pooled standard errors of observations was used as a weight factor in the analysis

[2] BW = body weight

Table 13. Effects of corn DDGS dietary inclusion on growth performance responses of pigs (summary of 27 studies since 2010)

		Responses to dietary corn DDGS[1]		
	N	**Increased**	**Reduced**	**Not changed**
ADG	106	0	30	76
ADFI	106	10	29	67
Gain:Feed	106	7	28	71

[1] The number of significant and non-significant results

As shown in **Table 14**, 72 of the 106 total observations in these studies evaluated growth performance responses to pigs fed reduced-oil DDGS. Pigs fed reduced-oil DDGS had slightly greater, but still small, overall reductions in ADG (-2.6 percent) and gain:feed (-1.1 percent) compared to the small reduction in ADG (-1.7 percent) and gain:feed (-1.3 percent) from feeding high-oil (greater than 10 percent crude fat) DDGS sources. These small differences may be due to using inaccurate energy and digestible amino acid values for reduced-oil DDGS sources when formulating experimental diets. Overall, the majority of observations in these 27 studies showed no change in ADG between feeding high-oil (88 percent) or reduced-oil (64 percent), ADFI (56 percent for high-oil, 67 percent for reduced-oil) and gain:feed (62 percent for high-oil, 69 percent for reduced-oil) DDGS (**Table 15**).

Although the majority of studies (22 out of 27) used the ME system compared with the NE system (**Table 16**) to formulate diets, it appears that the use of the NE system resulted in a slightly greater, but still small, reduction in ADG (-2.6 percent), ADFI (-1.8 percent), but less reduction in gain:feed (-0.4 percent) compared with using the ME system (-2.3, -0.5, and -1.5 percent, respectively). These small differences are not of great practical consequences and are likely a result of using less well-defined NE values for the DDGS sources fed in these studies. Again, the majority of observations showed no change (**Table 17**) in ADG (71 percent for ME, 76 percent for NE), ADFI (64 percent for ME, 62 percent for NE), and gain:feed (59 percent for ME, 100 percent for NE).

Table 14. Effects of feeding high-oil (greater than 10 percent) and reduced-oil (less than 10 percent) corn DDGS on growth performance responses of pigs (summary of 27 studies since 2010)[1]

	DDGS – control (expressed as %)					
	ADG	**ADFI**	**Gain:Feed**	**Initial BW, kg**	**Final BW, kg**	**Feeding days**
High-oil DDGS						
Observations	34	34	34	34	34	34
Studies	9	9	9	9	9	9
Mean	-1.7**	-0.3	-1.3**	48.6	119.5	75
Minimum	-9.0	-7.9	-7.6	30.3	81.7	43
Maximum	3.2	8.2	3.7	49.7	134.9	96
Reduced-oil DDGS						
Observations	72	72	72	72	72	72
Studies	19	19	19	19	19	19
Mean	-2.6**	-0.8*	-1.1**	9.4	20.2	25
Minimum	-12.3	-12.8	-17.7	6.7	17.5	20
Maximum	4.1	18.0	6.5	105.7	132.9	120

**Means differ from 0 (P less than 0.05)

*Means differ from 0 (P less than 0.10)

[1] The inverse of pooled standard errors of observations was used as a weight factors in the analysis

[2] BW = body weight

Table 15. Comparison of growth performance responses from feeding diets containing high-oil (greater than 10 percent crude fat) and reduced-oil (less than 10 percent crude fat) corn DDGS of pigs (summary of 27 studies since 2010)

		Responses to high-oil corn DDGS[1]		
	N	**Increased**	**Reduced**	**Not changed**
ADG	34	0	4	30
ADFI	34	9	6	19
Gain:Feed	34	1	12	21
		Responses to reduced-oil corn DDGS[1]		
	N	**Increased**	**Reduced**	**Not changed**
ADG	72	0	26	46
ADFI	72	1	23	48
Gain:Feed	72	6	16	50

[1] The number of significant and non-significant results

Table 16. Effects of using the metabolizable energy (ME) vs. net energy (NE) system in formulating corn DDGS diets on growth performance responses of pigs (summary of 27 studies since 2010)[1]

	DDGS – control (expressed as percent)					
	ADG	**ADFI**	**Gain:Feed**	**Initial BW, kg**	**Final BW, kg**	**Feeding days**
ME						
Observations	85	85	85	85	85	85
Studies	22	22	22	22	22	22
Means	-2.3**	-0.5	-1.5**	48.6	119.5	75
Minimum	-12.3	-12.8	-17.7	6.7	17.5	134.9
Maximum	4.1	18.0	6.5	100.6	134.9	96
NE						
Observations	21	21	21	21	21	21
Studies	5	5	5	5	5	5
Means	-2.6**	-1.8**	-0.4	9.4	20.2	25
Minimum	-9.0	-7.9	-4.9	29.1	106.2	20
Maximum	3.2	6.9	3.5	105.7	130.0	93.0

**Means differ from 0 (P less than 0.05)

[1] The inverse of pooled standard errors of observations was used as a weight factor in the analysis

Table 17. Effects of using the metabolizable energy (ME) vs. net energy (NE) system in formulating corn DDGS diets on growth performance responses of pigs (summary of 27 studies since 2010)[1]

		Responses to using ME content of corn DDGS[1]		
	N	**Increased**	**Reduced**	**Not changed**
ADG	85	0	25	60
ADFI	85	10	31	54
Gain:Feed	85	7	28	50
		Responses to NE content of corn DDGS[1]		
	N	**Increased**	**Reduced**	**Not changed**
ADG	21	0	5	16
ADFI	21	0	8	13
Gain:Feed	21	0	0	21

[1] The number of significant and non-significant results

Although there were fewer observations for growth performance responses of nursery pigs (n = 19) compared with growing-finishing pigs (n = 87), the relative decrease in ADG and gain:feed when feeding DDGS diets appeared to be greater in nursery pigs (**Table 18**). However, among these observations, 68 percent of responses represented no change in ADG, 89 percent showed no change in ADFI and 74 percent of observations showed no effect on gain:feed (**Table 19**). Therefore, it appears that the greater magnitude of performance reductions in nursery pigs fed DDGS diets were a result of the negative responses in one study. Therefore, if nursery diets are formulated with accurate digestible nutrient composition data for DDGS, no change in growth performance compared with feeding control diets will be observed the majority of the time.

Table 18. Effects of feeding corn DDGS to nursery vs. growing-finishing pigs on growth performance responses (summary of 28 studies since 2010)[1]

	Pig age DDGS – control (expressed as %)		
	< 35 kg BW	**> 35 kg BW**	**Standard Error**
Observations	19	87	-
Studies	4	24	-
ADG	-6.3**	-2.2**	1.05
ADFI	-1.8	-3.7**	1.52
Gain:Feed	-3.7**	1.4	1.28

**Means differ from 0 (P less than 0.05)

[1] The inverse of pooled standard errors of observations was used as a weight factor in the analysis

Table 19. Effects of feeding corn DDGS to nursery vs. growing-finishing pigs on growth performance responses (summary of 27 studies since 2010)[1]

		Responses of nursery pigs fed DDGS[1]		
	N	**Increased**	**Reduced**	**Not changed**
ADG	19	0	6	13
ADFI	19	0	2	17
Gain:Feed	19	0	5	14
		Responses of grower-finisher pigs fed DDGS[1]		
	N	**Increased**	**Reduced**	**Not changed**
ADG	87	0	24	63
ADFI	87	10	27	50
Gain:Feed	87	7	23	57

[1] The number of significant and non-significant results

In the U.S., diet inclusion rates of corn DDGS in growing-finishing pigs diets typically range from 20 to 30 percent, but because of the substantial feed cost savings often provided by DDGS, several large pork production companies are beginning to add DDGS at levels up to 60 percent of the diet to achieve even greater feed cost savings, even though growth performance may be slightly reduced. Acceptable pork fat quality can be achieved when feeding diets contain greater than 30 percent DDGS in the U.S. by using a recently approved feed additive (Liponate™; Nutriquest, Mason City, Iowa) to prevent carcass fat depots from becoming softer, or by feeding reduced-oil DDGS and withdrawing it from the diet for a few weeks before slaughter. In contrast, many nutritionists in the DDGS export market are often reluctant to use more than 20 percent DDGS in growing-finishing diets because of concerns of reduced growth performance. As a result, significant feed cost savings are not realized by using lower dietary DDGS inclusion rates. However, using the ME and SID amino acid prediction equations to accurately estimate energy and digestible amino acid content of the DDGS source being fed, should be used to achieve no reductions in growth performance when feeding diets containing up to 30 percent DDGS for growing-finishing pigs. This will also require using supplemental synthetic amino acids and fat or oil to meet the requirements of pigs. A summary of growth performance responses at various dietary DDGS inclusion rates is shown in **Table 20**. Negligible effects of feeding diets containing up to 20 percent on ADG, ADFI and gain:feed have been observed when feeding reduced-oil DDGS to nursery and growing finishing pigs. In fact, the majority of responses for ADG (70 percent), ADFI (68 percent) and gain:feed (62 percent) showed no change when feeding diets containing 25 to 30 percent DDGS. However, of the limited observations (n = 9), about half showed no change in ADG and ADFI, while the other half showed about a 2.4 to 2.8 percent reduction, respectively. However, the magnitude of these negative responses is small (e.g. 0.90 vs. 0.92 kg/day ADG between DDGS and control diets).

There are several reasons that may explain why feeding diets containing high inclusion rates (greater than 30 percent) of DDGS in diets for swine may result in small decreases in growth performance of pigs. First, DDGS has much greater fiber content (35 to 45 percent NDF) compared with corn and soybean meal. Fiber reduces the ME and NE content of swine diets and also can limit feed intake due to gut fill. As a result, pigs in the nursery and early grower stages may not be able to physically consume enough of a high fiber diet to meet their energy requirement. Research to improve fiber utilization and ME and NE content of DDGS diets by supplementing diets with feed enzymes, has become one of the most widely researched topics in recent years (see **Chapter 25**). Unfortunately, the use of commercially available carbohydrases and proteases in DDGS diets have not provided consistent of substantial improvements in fiber digestibility and energy content for pigs. Secondly, use of accurate ME or NE values for DDGS in diet formulation is essential. Many nuritionists are unaware of the opportunity to use accurate prediction equations to estimate the variable energy (ME) content in DDGS (Urriola et al., 2014) DE, and ME among sources of corn DDGS. Use of ME values derived from these equations will ensure optimum diet formulations to minimize suboptimal feed intake and growth. Furthermore, standardized ileal digestibility of amino acids are affected by the fiber concentration in DDGS (Urriola and Stein, 2010), which has led to conducting a meta-analysis of published data to provide accurate prediction equations to dynamically estimate the SID amino acid values for corn DDGS based on total amino acid and NDF content of DDGS sources (Zeng et al., 2017)g/kg. In fact, some commercial

Table 20. Effects of diet inclusion rate of corn DDGS on growth performance responses of pigs (summary of 25 studies[1] since 2010)

	DDGS - control		Response to dietary corn DDGS		
DDGS inclusion rate	**Mean %**	**N**	**Increased**	**Reduced**	**Not changed**
< 12.5%					
ADG	-0.95	13	0	2	11
ADFI	0.15	13	0	2	11
Gain:Feed	-0.60	13	1	1	11
15 to 20%					
ADG	-0.91*	27	0	3	24
ADFI	-0.65	27	6	6	15
Gain:Feed	-0.66	27	3	7	17
25 to 30%					
ADG	-3.20**	47	0	14	33
ADFI	-0.24	47	4	11	32
Gain:Feed	-2.14**	47	1	17	29
> 30%					
ADG	-2.44**	9	0	5	4
ADFI	-2.28**	9	0	4	5
Gain:Feed	-0.18	9	0	3	6

**Means differ from 0 (P less than 0.05)

*Means differ from 0 (P less than 0.10)

[1] Data from Jha et al. (2015) were omitted from the analysis because DDGS diets contained barley (16 percent), extruded full-fat flax seed and field peas (20 percent). Data from Benz et al. (2011) were omitted from analysis because DDGS diets were supplemented with peroxidized oil, which resulted approximate 20 times greater iodine value in the DDGS diets compared to the control diet

companies (e.g. Nutriquest, Cargill and Evonik) offer services to nutritionists to estimate the SID of amino acids for DDGS. Therefore, the prediction equations described in this chapter, as well as commercially available services should be used by nutritionists to estimate the ME, NE and SID amino acid content among sources of corn DDGS.

Other aspects of DDGS composition that may affect growth performance of pigs when feeding high (greater than 30 percent) dietary inclusion rates to pigs that have been less studied. Corn DDGS contains high concentrations of fiber, and high dietary fiber increases the threonine requirement of pigs (Zhu et al., 2005). Mathai et al. (2016) showed that the threonine requirement, expressed as a ratio to lysine, was increased for pigs consuming diets with soybean hulls and pea fiber compared with pigs consuming a low fiber diet. Depending on fiber composition, endogenous losses of threonine, and the subsequent requirement of threonine is likely increased when feeding diets containing high concentrations of DDGS (Blank et al., 2012). Based on data from Huang et al. (2017) and Saqui-Salces et al. (2017a) and the NRC (2012) model, the estimated threonine endogenous losses (as a percentage of the requirement) from feeding a high DDGS diets is 7.7 percent compared to feeding a corn-soybean meal diet (3.2 percent). As a result, the optimal SID Thr to SID ratio in DDGS diets may be 61 percent compared with 59 percent in corn-soybean meal diets.

In addition to the role of DDGS fiber on endogenous losses of Thr, DDGS also contains a 3.3 times greater concentration of leucine than soybean meal, and the high proportion of leucine relative to isoleucine (1.12×) and valine (1.47×) may result in a deficiency of isoleucin and valine when feeding high (greater than 30 percent) DDGS diets with reduced soybean meal content to pigs. These three branch chain amino acids share the same degradation pathway through the α-keto-acid dehydrogenase complex (BCKDC). This enzyme is inactivated by a kinase, and its activity is modified by the product of catabolism of leucine (Harris et al., 2004). Consequently, excess intake of leucine increases catabolism of isoleucine and valine (Wiltafsky et al., 2010; Gloaguen et al., 2012) Although Htoo et al. (2017) determined the isoleucine and valine requirements of pigs fed excess leucine (greater than 160 of SID Leu:Lys), diets containing DDGS have different proportions of leucine to isoleucine and valine, and the validity of using these branch chain amino acid ratios when formulating DDGS diets has not been evaluated in large commercial swine production systems. The effect of excess dietary leucine is primarily a reduction in feed intake. Excess leucine content in DDGS, and subsequent catabolism of isoleucine and valine can be mitigated by allowing crude protein from soybean meal to meet the amino acid requirement, and avoiding the use of high amounts of synthetic lysine and other amino acids (less than 0.15% Lys HCl; Stein and Shurson, 2009). However, the current relatively low price of synthetic amino acids and DDGS supports reducing the use of soybean meal and increasing the use of synthetic amino acids in swine diets containing greater than 30% DDGS. Furthermore, the effects of excess dietary leucine on catabolism of isoleucine and valine may also be reduced by adding synthetic isoleucine to the diet to achieve adequate amino acid balance. Studies are underway to evaluate branch chain amino acid balance in diets containing greater than 30% DDGS for nursery and growing-finishing pigs.

Feeder Design and Feeding Management

There are a variety of commercial feeder designs used in commercial swine operations that have various advantages and disadvantages. Bergstrom et al. (2012) evaluated using conventional dry feeders compared with wet-dry feeders and various feeder adjustment openings on growth performance and carcass characteristics of growing pigs. These researchers observed that pigs fed using the wet-dry feeders had greater ADG, ADFI, hot carcass weight and carcass backfat thickness. They also observed that the wet-dry feeder was more sensitive to differences in feeders adjustment compared to the conventional dry feeders. Results from this study led to a subsequent study, where Bergstrom et al. (2014) evaluated pig growth performance and carcass characteristics of growing finishing pigs fed diets containing 20 or 60 percent DDGS using wet-dry or conventional dry feeders (**Table 21**). A total of 1,080 pigs were used in this study, which was conducted on a commercial farm. Pigs were placed in 40 pens 927 pigs/pen) containing either wet-dry or conventional dry feeders. Diets were formulated on a ME basis using 3,420 kcal/kg ME for DDGS containing greater than 10 percent oil. Standardized ileal digestibility values from Stein et al. (2006) were used for DDGS when formulating the diets. All other ME and SID amino acid values for other ingredients were obtained from NRC (1998). Growth rate, ADFI and final body weight were greater for pigs fed using the wet-dry feeders compared with those fed using the conventional dry feeders, but gain:feed was greater for pigs fed using the conventional dry feeders. As a result, pigs fed using wet-dry feeders had heavier hot carcass weight, greater carcass backfat depth, less carcass fat free lean and lower jowl fat iodine value than pigs fed with the conventional dry feeders. Feeding the 60 percent DDGS slightly reduced ADG, gain:feed,

Table 21. Effects of dietary DDGS inclusion level and feeder design on growth performance and carcass characteristics of growing-finishing pigs (adapted from Bergstrom et al. 2014)

	Feeder Design			
	Wet-dry		Conventional dry	
	20% DDGS	60% DDGS	20% DDGS	60% DDGS
Growth performance, d 0 to 99				
ADG[1,2], kg	0.95	0.92	0.88	0.86
ADFI[1], kg	2.59	2.59	2.28	2.31
Gain:Feed[1,2]	0.367	0.355	0.384	0.382
BW[1], kg	129.2	126.9	122.6	121.3
Carcass characteristics				
Hot carcass weight[1,2], kg	96.6	93.5	90.9	89.8
Carcass yield %	74.9	75.1	74.9	75.2
Backfat depth[1,2], mm	19.0	18.1	16.7	16.2
Loin muscle depth, cm	5.96	5.89	6.10	5.99
Fat-free lean index[1,2] %	49.5	50.0	50.6	50.8
Jowl fat iodine value[1,2]	72.1	80.4	73.5	81.9

[1] Feeder design effect (P less than 0.05)

[2] Diet DDGS inclusion rate effect (P less than 0.05)

and tended to reduce final body weight compared with feeding the 20 percent DDGS diets. Feeding 60 percent DDGS diets resulted in lower hot carcass weight, backfat depth, but greater carcass fat free lean and jowl fat iodine value, but had no effect on carcass yield. These results show that feeder design can have significant effects on growth performance and carcass composition of pigs fed DDGS diets, and that extremely high diet inclusion rates (60 percent) of DDGS may reduce ADG and hot carcass weight, but improve gain:feed and percentage of carcass lean compared with feeding diets containing 20 percent DDGS to growing finishing pigs.

Weber et al. (2015) conducted a study to evaluate growth performance of pigs fed 30 or 60 percent DDGS diets using different feeder space allowances (**Table 22**). Diets were formulated to be isocaloric by adding varying amounts of choice white grease, and metabolizable energy content of the DDGS source used was estimated using the equation from Noblet and Perez (1993). A 5-phase late-nursery and growing-finishing feeding program was used, and dietary DDGS inclusion rates were 27.5, 30.0, 32.5, 32.5 and 26.3 percent in phase 3, 4, 5, 6 and 7, respectively. Dietary inclusion rates of DDGS for the 60 percent DDGS treatment were 30.0, 59.9, 59.9, 59.9 and 30.0 percent in phase 3, 4, 5, 6 and 7, respectively. There were no interactions between feeder space and DDGS inclusion rate, indicating that feeder space does not affect growth performance and carcass characteristics of pigs fed with 30 percent or 60 percent DDGS diets during the growing-finishing period. Furthermore, there were no differences in final body weight, ADG, ADFI and gain:feed of pigs fed the 30 percent or 60 percent DDGS diets. However, pigs fed the 30 percent DDGS diets had slightly heavier hot carcass weight and greater carcass yield and loin depth at slaughter compared with pigs fed the 60 percent DDGS diets. The results from this study suggest that feeder space allowances provided during the growing-finishing phase had no effect on growth performance or carcass characteristics of pigs fed 30 or 60 percent DDGS diets, but feeding the 60 percent DDGS diets slightly reduced carcass weight, yield and loin depth compared with pigs fed 30 percent DDGS diets.

Table 22. Overall growth performance and carcass characteristics of growing-finish pigs using different feeder space allowances and diet inclusion rates of DDGS during phases 4, 5, and 6 (adapted from Weber et al. 2015)

	Feeder space, cm/pig			Diet[1]	
	4.1	**4.9**	**5.7**	**30 % DDGS**	**60 % DDGS**
No. pigs/pen	31	31	31	31	31
Body weight, kg					
Day 0	29.9	29.8	29.8	30.3[a]	29.3[b]
Market	121.5	122.2	122.9	122.4	121.9
CV %					
Day 61	18.3	17.9	17.2	18.0	17.6
Day 152	11.1	11.0	9.8	10.9	10.5
ADG, kg	0.91	0.91	0.92	0.91	0.92
ADG carcass, kg	0.69	0.70	0.71	0.71	0.69
ADFI, kg	2.06	2.04	2.04	2.07	2.03
Gain:Feed[2]	0.44	0.45	0.45	0.44	0.45
Gain:Feed[3]	0.34	0.34	0.35	0.34	0.34
Days to market	155.0	156.2	155.8	156.1	155.3
Carcass characteristics					
No. pens	10	10	10	15	15
HCW, kg	92.7	93.4	93.8	93.9[a]	92.7[b]
Yield %	75.2	75.7	76.1	76.1[a]	75.2[b]
Backfat depth, mm	12.8	12.7	12.8	12.6	12.9
Loin depth, mm	63.6	64.4	63.7	64.9[a]	62.9[b]

[a,b] Means within a row and main effect without a common superscript are different (P less than 0.05)

[1] Diet inclusion rate of DDGS during phases 4, 5 and 6

[2] Gain:Feed calculated using live ADG

[3] Gain:Feed calculated using carcass ADG

Myers et al. (2013) fed meal or pelleted diets containing 25 to 45 percent DDGS and 15 to 30 percent bakery meal to evaluate diet form on growth performance and carcass characteristics of growing finishing pigs (n = 1,290), in a five-phase feeding program using conventional dry or wet-dry feeders (**Table 23**). There was no diet form × feeder design interaction for ADG, but pigs fed pelleted diets had greater ADG than those fed meal diets. Pigs fed using the wet-dry feeders had greater ADG compared with those fed using conventional dry feeders. Pigs fed meal diets using dry feeders had reduced ADFI compared with pigs fed pelleted diets, but ADFI was not different between the two diet forms when fed using the wet-dry feeders. gain:feed was similar for pigs fed meal or pelleted diets using wet-dry feeders, but was reduced for pigs fed the pelleted diets using the dry feeder compared with pigs fed meal diets. There were no diet form × feeder design interactions, or differences between diet forms for any carcass characteristics, but pigs fed using the wet-dry feeder more backfat and lower percentage of carcass fat-free lean than pigs fed using dry feeders.

At certain times, fluctuations in DDGS price and availability may cause it to be used in swine diets intermittently during the growing-finishing phase to capture the greatest economic advantages. Furthermore, commercial feed mills may use multiple sources of DDGS with variable nutrient content and digestibility, which may influence growth performance and carcass composition if dynamic adjustments are not made in energy and amino acid content and digestibility when diets are formulated. Hilbrands et al. (2013) conducted two experiments to determine the effects on growth performance and carcass composition resulting from alternating diets with and without DDGS during the growing finishing phase. In the first experiment, pigs were fed using a three-phase feeding program using corn-soybean meal control diets, or 20 percent or 40 percent DDGS diets continuously or alternating every two weeks between control and 20 percent DDGS diets or control and 40 percent DDGS diets. As shown in **Table 24**, there were no differences in growth performance or carcass traits of pigs fed 20 percent DDGS diets continuously or fed 20 percent DDGS and control diets alternating every two weeks. However, when diets were alternated every two weeks between the 40 percent DDGS and control diets, hot carcass weight was reduced compared with all other dietary treatments.

In the second experiment conducted by Hilbrands et al. (2013), two sources of DDGS were obtained that had low or high SID amino acid digestibility. Metabolizable energy content of these sources were derived from ME prediction equations from Pedersen et al. (2007).The SID amino acid values from these sources were derived from the IDEA assay

Table 23. Effect of diet form and feeder design on growth performance and carcass composition in growing-finishing pigs fed DDGS diets (adapted from Myers et al., 2013)

	Conventional dry		Wet-Dry	
	Meal	**Pellet**	**Meal**	**Pellet**
Growth performance, day 0 to 91				
ADG[1,2], kg	0.84	0.85	0.89	0.91
ADFI[1,2], kg	2.29[a]	2.45[b]	2.50[b]	2.51[b]
Gain:Feed[1]	0.369[a]	0.349[c]	0.357[bc]	0.361[ab]
Body weight[2], kg	123.1	124.0	127.2	128.5
Pellet quality				
PDI	-	74.0	-	74.0
Fines %	-	36.6	-	36.6
Carcass characteristics				
Hot carcass weight, kg	91.7	92.7	94.1	93.8
Yield %	75.6	75.3	75.6	76.0
Backfat depth[2], mm	17.3	17.2	18.8	18.3
Loin depth, cm	6.19	6.05	5.97	5.93
Carcass fat-free lean index[2] %	50.4	50.4	49.7	49.9

[a,b]Means within a row without a common superscript are different (P less than 0.05)

[1]Diet form effect (P less than 0.07)

[2]Feeder design effect (P less than 0.01)

Table 24. Effects of dietary inclusion and removal of DDGS on growth performance and carcass composition of growing-finishing pigs (adapted from Hilbrands et al., 2013).

	Control diets fed continously	20% DDGS diets fed continously	Alternate between 20% DDGS and control diets	Alternate between 40% DDGS and control diets
Initial body weight, kg	51.3	51.3	51.3	51.4
Final body weight, kg	112.3^{xy}	112.2^{xy}	113.0^{x}	110.6^{y}
ADG, kg	0.87	0.87	0.88	0.85
ADFI, kg	2.70^{xy}	2.75^{x}	2.71^{xy}	2.63^{y}
Gain:Feed	0.323^{ab}	0.317^{a}	0.325^{b}	0.322^{ab}
Hot carcass weight, kg	83.8^{a}	83.6^{a}	84.3^{a}	81.1^{b}
Carcass yield %	74.8	74.6	74.6	73.8
10th rib backfat depth, mm	19.3	20.1	20.4	19.8
Loin muscle area, cm^2	48.8	48.3	48.2	47.6
Carcass lean %	54.4	54.0	53.8	54.2

^{a,b}Means within a row without a common superscript differ (P less than 0.05)

^{x,y}Means within a row without a common superscript differ (P less than 0.10)

(Novus International, St. Louis, MO), and SID amino acid values were obtained from NRC (1994). Values for ME and SID amino acids for corn and soybean meal were obtained from NRC (1998). All diets (corn-soybean meal control (CON), 40 percent DDGS with low digestible amino acids (LD) and 40 percent DDGS with high digestible amino acids (HD) were formulated on a SID amino acid basis and were fed in four phases. Six dietary treatments consisting of 1) CON diets fed continously, 2) LD diets fed continuously, 3) HD diets fed continuously, 4) LD and CON diets alternated by phase, 5) HD and LD diets alternated by phase, and 6) HD and LD diets alternated by phase (**Table 25**). Pigs fed LD and HD-LD had reduced ADG and lower final body weight compared with CON, and feeding LD resulted in lower ADFI than LD-CON and HD-CON, but gain:feed was not affected by dietary treatment. These results indicate that the SID amino acid content was likely overestimated by the IDEA assay when formulating diets. Pigs fed LD and HD-LD had lower hot carcass weight, yield and loin muscle area than the other dietary treatments. However, periodic inclusion and removal of 40 percent DDGS from diets did not adversely affect overall growth performance regardless of amino acid digestibility of the DDGS source fed. Furthermore, there were no differences in the percentage carcass lean among dietary treatments. Therefore, the results of these two experiments indicate that that alternating between corn-soybean meal and DDGS diets every two weeks does not have meaningful detrimental effects on growth performance or carcass composition.

Carcass Composition

Several studies (n = 20) have been published since 2010 to evaluate the effects of feeding corn DDGS diets on carcass composition of growing-finishing pigs, and overall responses for carcass yiled and percentage carcass lean are summarized in **Table 26 and 27** (Asmus et al., 2014; Coble et al., 2017; Cromwell et al., 2011; Davis et al., 2015; Duttlinger et al., 2012; Graham et al., 2014a,b,c; Hardry matteran, 2013; Jacela et al., 2011; Jha et al., 2013; Lee et al., 2013; McDonnell et al., 2011; Nemechek et al., 2015; Overholt et al., 2016; Pompeu et al., 2013; Salyer et al., 2013; Wang et al., 2012; Wu et al., 2016c; Ying et al., 2013). One of the most consistent effects of feeding DDGS diets is a slight reduction in carcass yield. The relatively high fiber content in DDGS increases the weight of the gastrointestinal tract resulting in lower carcass:live weight. From this meta-analysis, for every percentage unit increase of DDGS inclusion in growing-finishing pig diets, carcass yield was decreased by 0.022 percent (relative percentage). This effect appears to be related to DDGS oil content where feeding high-oil (greater than 10 percent) DDGS reduced carcass yield, but feeding reduced-oil DDGS diets resulted in no significant change in yield (**Table 27**). Use of either the NE or ME system in formulating DDGS diets resulted in similar reduction in carcass yield. However, the percentage of carcass fat-free lean is not affected by feeding diets containing high or reduced-oil DDGS or use of the ME versus NE systems.

Table 25. Effects of feeding diets containing 40 percent DDGS with low (LD) or high (HD) standardized ileal digestible amino acids continuously or alternated every two weeks with control (CON) diets on growth performance and carcass composition of growing-finishing pigs (adapted from Hilbrands et al., 2013)

	CON	LD-CON	HD-CON	LD	HD	HD-LD
Initial body weight, kg	33.2	33.2	33.2	33.2	33.2	33.2
Final body weight, kg	121.5^{ab}	121.6^{ab}	123.0^{a}	115.9^{c}	118.3^{bc}	117.8^{c}
ADG, kg	0.92^{ab}	0.92^{ab}	0.93^{a}	0.86^{c}	0.89^{bc}	0.88^{c}
ADFI, kg	2.70^{ab}	2.72^{a}	2.78^{a}	2.57^{b}	2.73^{ab}	2.68^{ab}
Gain:Feed	0.34	0.34	0.34	0.34	0.33	0.33
Lean gain/day, kg	0.395^{ab}	0.396^{ab}	0.405^{a}	0.362^{d}	0.383^{bc}	0.367^{cd}
Lean gain efficiency	0.15	0.15	0.15	0.14	0.14	0.14
Hot carcass weight, kg	93.3^{a}	92.3^{ab}	94.4^{a}	87.2^{c}	89.4^{bc}	88.5^{c}
Carcass yield %	76.2^{a}	75.8^{ab}	76.0^{ab}	74.7^{c}	75.1^{bc}	74.6^{c}
10th rib backfat depth, mm	21.3^{a}	19.9^{ab}	20.4^{ab}	18.9^{ab}	18.1^{b}	19.8^{ab}
Loin muscle area, cm^2	44.7^{a}	44.7^{a}	45.3^{a}	40.4^{b}	42.7^{ab}	40.6^{b}
Carcass lean %	51.8	52.1	52.1	51.3	52.3	50.8

^{a,b,c,d}Means within a row without a common superscript differ (P less than 0.05)

Table 26. Effects of feeding corn DDGS diets on carcass yield and percentage of fat-free lean of growing-finishing pigs (summary of 20 studies[1] since 2010)

Item	DDGS – control (absolute differences %)		Initial BW, kg	Final BW, kg	Feeding days
	Yield	Fat-free lean			
Observations	75	55	75	75	75
Studies	20	16	20	20	20
Mean	-0.87**	0.05	46.7	120.3	76.5
Minimum	-2.1	-1.6	23.4	86.9	20
Maximum	0.7	1.6	105.7	1.4.9	120

**Means differ from 0 (P less than 0.05)

[1] The inverse of pooled standard errors of observations was used as a weight factor in the analysis

Table 27. Effects of oil content of corn DDGS, and formulating diets on a ME vs. NE system, on carcass yield and percentage carcass fat-free lean of pigs (summary of 20 studies[1] since 2010)

	DDGS oil content		SE	Energy system		SE	P value	
	> 10%	< 10%		ME	NE		Oil content	Energy system
Observations	30	45		60	15			
Studies	8	13		16	4			
Yield	-0.79**	-0.42	0.17	-0.49**	-0.72**	0.16	0.034	0.139
Fat-free lean	0.20	-0.16	0.23	0.24	-0.18	0.14	0.220	<0.01

**Means differ from 0 (P less than 0.05)

*Means differ from 0 (P less than 0.10)

[1] The least squares means are reported. The inverse of pooled standard errors of observations was used as a weight factor in the analysis.

[2] Every percentage unit increase of DDGS inclusion in growing-finishing pig diets resulted in a 0.022 percent decrease (relative percentage) in the carcass yield

Pork fat quality

It has been well documented that feeding corn-soybean meal diets containing increasing dietary levels of DDGS to growing-finishing pigs results in reduced pork fat firmness (Stein and Shurson, 2009; Xu et al., 2010a,b; Benz et al., 2010; Graham et al., 2014a,b; Davis et al., 2015). Pork fat firmness has been commonly measured using iodine value (IV), which is the ratio of unsaturated to saturated fatty acid content in jowl, backfat and belly fat. Several feeding management strategies have been developed, and can be effective in managing fat quality in pork carcasses. These strategies include gradually reducing dietary DDGS level before harvest (Harris et al., 2018), withdrawal of DDGS from the diet for more than three weeks before harvest (Jacela et al., 2009; Xu et al., 2010b; Hilbrands et al., 2013), feeding reduced-oil DDGS (Dahlen et al., 2011; Wu et al., 2016a), and formulating diets using carcass fat IV prediction equations (Wu et al. 2016b).

Numerous regression equations have been developed to predict IV in jowl, backfat, or belly fat based on IV product (IVP) of diets (Madsen et al., 1992; Boyd et al., 1997; Bergstrom et al., 2010; Estrada Restepo, 2013), linoleic acid (C18:2) intake (Averette Gatlin et al., 2002; Benz et al., 2011; Kellner, 2014) and percentage of DDGS in the diet (Cromwell et al., 2011; Estrada Restrepo, 2011). Most recently, Paulk et al. (2015) developed IV prediction equations based on dietary essential fatty acid content, days fed initial and final diets, net energy content of final diet and carcass backfat depth.

Wu et al. (2016) compared the precision and accuracy of predicting backfat IV using these equations and found that the Paulk et al. (2015) equation resulted in the best prediction with the least error and bias (**Table 28**). Overall, these results showed that reduced oil content of DDGS generally reduced the negative impact of feeding DDGS diets on pork fat quality by reducing the IV of carcass fat depots. However, the magnitude of this improvement was not proportional to the amount of dietary lipid intake and may be affected by differences in the digestibility of oil in DDGS. It is important to remember that fatty acid composition varies among carcass fat depots. Jowl fat has a greater IV than backfat and belly fat, but backfat appears to be the most sensitive to changes in dietary lipid content than jowl fat and belly fat. Use of published carcass fat IV prediction equations resulted in variable precision and accuracy in estimating IV of carcass fat depots. It appears that adding additional factors such as dietary energy content, growth performance and carcass composition measures, as indicated in the Paulk et al. (2015) equations, results in improved carcass fat IV predictions than using those based only on characteristics and quantity of dietary lipids. Using the percentage of DDGS in diets as a predictor of carcass fat depot IV results in the poorest prediction. However, the magnitude of the prediction error and bias of these equations needs to be reduced to achieve more predictable carcass fat IV responses when feeding DDGS diets to growing-finishing pigs.

Table 28. Comparison of prediction equations for estimating iodine value (IV) of carcass backfat, jowl fat, belly fat and the average IV of the three carcass fat depots (adapted from Wu et al., 2016)

Fat depot	Equation	R^2	Prediction error[1]	Bias[2]	Reference
Backfat					
	47.1 + 0.14 × IVP[3] intake/day	0.86	6.43	-4.95	Madsen et al., 1992
	52.4 + 0.315 × diet IVP	-	4.60	-2.15	Boyd et al., 1997
	51.946 + 0.2715 × diet IVP	0.16	6.45	-5.05	Benz et al., 2011
	35.458 + 14.324 × diet C18:2 %	0.73	8.36	-1.08	Benz et al., 2011
	64.5 + 0.432 ×DDGS in diet %	0.92	8.26	7.10	Cromwell et al., 2011
	60.13 + 0.27 × diets IVP	0.81	5.04	3.05	Estrada Restrepo, 2013
	70.06 + 0.29 × DDGS in diet %	0.81	9.19	8.00	Estrada Restrepo, 2013
	84.83 + (6.87 × IEFA) – (3.90 × FEFA) – (0.12 × Id) – (1.30 × Fd) – (0.11 × IEFA × Fd) + (0.048 × FEFA × Id) + (0.12 × FEFA × Fd) – (0.006 × FNE) + (0.0005 × FNE × Fd) – (0.26 × BF)	0.95	4.01	-0.84	Paulk et al., 2015[4]
Jowl fat					
	56.479 + 0.247 × diet IVP	0.32	4.92	-3.69	Benz et al., 2011
	47.469 + 10.111 × diet C18:2 %	0.90	5.57	-1.37	Benz et al., 2011
	64.54 + 0.27 × diet IVP	0.81	6.55	5.66	Estrada Restrepo, 2013
	72.99 + 0.24 × DDGS in diet %	0.81	8.33	7.38	Estrada Restrepo, 2013
	85.50 + (1.08 × IEFA) + (0.87 × FEFA) – (0.014 × Id) – (0.05 × Fd) + (0.038 × IEFA × Id) + (0.054 × FEFA × Fd) – (0.0.0066 × INE) + (0.071 × IBW) – (2.19 × ADFI) – (0.29 × BF)	0.93	4.73	-3.37	Paulk et al., 2015[4]
Belly fat					
	58.32 + 0.25 × diet IVP	0.74	3.43	1.41	Estrada Restrepo, 2013
	67.35 + 0.26 × DDGS in diet %	0.75	6.66	5.53	Estrada Restrepo, 2013
	106.16 + (6.21 × IEFA) – (1.50 × Fd) – (0.11 × IEFA × Fd) – (0.012 × INE) + (0.00069 × INE × Fd) – (0.18 × HCW) – (0.25 × BF)	0.94	3.27	1.73	Paulk et al., 2015[4]
Average of three depots					
	58.103 + 0.2149 × diet IVP	0.93	3.93	-2.23	Kellner, 2014
	58.566 + 0.1393 × C18:2 intake/day, g	0.94	6.17	-4.90	Kellner, 2014

[1] Prediction error (smaller value indicates greater precision of the equation)

[2] Prediction bias (smaller absolute value indicates greater accuracy of the equation; negative value indicates underestimation and positive values indicate overestimation)

[3] IVP = iodine value product = dietary IV × percent dietary lipids × 0.10 (Madsen et al., 1992)

[4] Abbreviations in equations are: I = initial diet, F = final diet, d = days diet is fed, EFA = essential fatty acids (C18:2 and C18:3 %), NE = net energy (kcal/kg), BW = body weight (kg), ADFI = average daily feed intake (kg), HCW = hot carcass weight (kg), BF = backfat depth (mm)

Pork lean quality

Several studies have been conducted to evaluate pork lean quality of pigs fed DDGS diets. Leick et al. (2010) fed diets containing 0, 15, 30, 45 and 60 percent DDGS with and without 5 mg/kg ractopamine to growing finishing pigs to evaluate meat quality. Increasing dietary levels of DDGS had no effect on loin pH, subjective and objective color, marbling or fat content, but decreased subjective marbling score, firmness, and increased drip loss. Furthermore, increasing dietary DDGS content decreased belly weight, length, thickness, firmness and L* and increased belly cook loss. Belly and jowl fat IV were increased, resulting from a decrease in monounsaturated:polyunsaturated fatty acid content. Loin TBARS was not affected at 0, 7 or 14 days of storage, but on day 21, TBARS of loins from pigs fed 30, 45 and 60 percent DDGS was increased compared to loins from pigs fed zero and 15 percent DDGS diets. These results suggest that feeding diets containing up to 60 percent DDGS to growing-finishing pigs has minimal effects on loin quality, but decreases belly quality, bacon processing characteristics and fat stability.

McClelland et al. (2012) fed growing-finishing pigs diets containing 0, 15, 30 or 45 percent DDGS diets. Results showed that increasing dietary levels of DDGS increased the concentrations of polyunsaturated fatty acids in carcass fat, which subsequently increased carcass fat IV and reduced belly firmness, but had no effect on slicing yield of cured bellies, quality of fresh bacon slices or eating quality of bacon, sausage or loin chops.

Wang et al. (2012) fed diets containing 0, 15 or 30 percent DDGS, supplemented with 10 or 210 IU/kg, to growing-finishing pigs and reported that feeding DDGS decreased the proportion of saturated fatty acids, and increased the proportion of unsaturated and polyunsaturated fatty acids in adipose and muscle. Increasing the dietary vitamin E content increased the concentration of α-tocopherol in adipose and muscle tissues, and reduced the concentration of total volatile basic nitrogen in vacuum-package fresh loins, which was increased by feeding increasing dietary levels of DDGS. The addition of DDGS to the diet resulted in a increase in TBARS of pork loins on day 13 of storage, but loins from pigs feed DDGS diets with 210 IU/kg vitamin E had significantly reduced TBARS in loins on day 4, 7, 10 and 13 of storage. These data suggest that although feeding diets containing DDGS have some adverse effects on storage shelf life of fresh pork loins, supplementing diets with 210 IU/kg of vitamin partially prevented these effects.

Ying et al. (2013) fed 0 or 30 percent DDGS diets in phase 1, 2, and 3, and 0 or a 20 percent DDGS diet during phase 4, with 0, 50, or 100 mg/kg L-carnitine to growing-finishing pigs to determine the effects on growth performance, carcass traits, and loin and fat quality. There were no DDGS × L-carnitine interactions for any carcass traits, but pigs fed increasing diet concentrations of L-carnitine had greater hot carcass weight, carcass yield, and backfat depth. Feeding L-carnitine increased loin purge loss while feeding DDGS tended to reduce loin marbling scores. Loin chops from pigs fed 50 mg/kg L-carnitine and DDGS had reduced shear force values compared with pigs fed diets containing 0 or 100 mg/kg L-carnitine. Increasing L-carnitine in DDGS diest resulted in increased fresh loin color scores. The concentrations of C18:2n-6 and C20:20 in jowl fat were reduced by feeding increasing levels of L-carnitine in DDGS diets, but not in diets containing no DDGS. These results suggest that feeding DDGS diets containing 50 mg/kg L-carnitine improved hot carcass weight and reduced linoleic acid content of jowl fat.

Overholt et al. (2016b) fed pelleted or meal diets containing 0 or 30 percent DDGS diets to fresh belly characteristics, fat quality, and bacon slicing yields of finishing pigs. Feeding the 305 DDGS diets reduced belly thickness, flop distance, and initial belly weight, while increasing belly fat IV by 7.1 units, compared with feeding 0 percent DDGS diets. However, feeding DDGS diets had no effect on bacon slice yields or slices per kg. These results suggest that although feeding 30 percent DDGS diets resulted in thinner, softer belies than pigs fed no DDGS, and feeding meal or pelleted 30 percent DDGS diets had no effect on commercial bacon slicing yield.

Feeding DDGS diets to immunological castrates

Physical castration of male pigs has been a common practice in many countries around the world for decades, and is done to reduce the occurrence of aggressive and sexual behaviors of male pigs and prevent the development of an unpleasant odor, known as boar taint, in pork from male pigs. However, while physical castration is effective in eliminating boar taint in pork, it results in lower feed efficiency, less carcass lean, and increased preweaning mortality. Furthermore, some countries such as the United Kingdom, Ireland and Australia no longer allow physical castration of male pigs due to animal welfare concerns. As a result, Zoetis (Florham Park, New Jersey) has developed and markets an injectable immunological castration product called Improvest (U.S. and Canada), Improvac (Australia and New Zealand), Innosure or Vivax, and is registered in 63 countries and has been used for more than 10 years in more than 50 million pigs worldwide (Bradford and Mellencamp, 2013). The U.S. Food and Drug Administration (FDA) has approved this product as safe to use, and pork derived from Improvest treated pigs is safe to eat because there are no residues that can affect human health. Furthermore, there are no export restrictions of pork from immunologically castrated pigs from using this product (Bradford and Mellencamp, 2013). Its use requires two injections, with the first aDMInistration serving as the priming dose for the male pig's immune system and the second dose, admInistered three to 10 weeks before market, causes suppression of testicular function. Immunological castration of male pigs has many advantages over physical castration including improved growth rate and feed conversion, greater carcass lean and less backfat and can dramatically improve profitability by more than $10 per market hog in the U.S. Therefore, recent studies have been conducted to determine the effects of feeding DDGS diets to immunologically castrated pigs on growth performance, carcass characteristics and meat and pork fat quality.

Asmus et al. (2014b) fed physically or immunologically castrated pigs one of three dietary treatments consisting of 0 percent DDGS, 30 percent DDGS, or 30 percent DDGS diets through day 75 and no DDGS to day 125 (market). Immunologically castrated pigs had reduced carcass yield and feed intake, regardless of dietary treatment, compared with physical castrates, but had improved ADG and gain:feed. Carcasses from immunologically castrated pigs had increased IV of carcass fat depots, but increasing the length of feeding duration before market after the second Improvest injection resulted in carcass fat IV to be similar to that of physical castrates. Regardless of castration method, withdrawing DDGS from the diet before slaughter reduced the negative impact on carcass yield and improved carcass fat firmness.

Little et al. (2014) evaluated belly quality of finishing pigs fed 0 or 30 percent DDGS diets, and withdrawing DDGS from the diet 5 weeks before slaughter improved belly firmness in immunological castrates (IC) and physical castrates (PC). There were no differences in bacon aroma, off-flavor, flavor or saltiness between IC and PC pigs slaughtered five or seven weeks after the second improves dose regardless of DDGS feeding program. These results indicate that immunological castration was as effective as physical castration in eliminating boar taint in bacon when feeding 30 percent DDGS diets or withdrawing DDGS from the diet before slaughter at five or seven weeks after aDMInistering the second dose of Improvest.

Similarly, Tavárez et al. (2014) evaluated carcass cutability and commercial bacon slicing yields of PC and IC barrows slaughtered at two time points and fed 0 or 30 percent DDGS diets and withdrawing DDGS from the diet after the second Improvest dose until slaughter. Carcass traits, cutting yields, and fesh belly characteristics were minimally affected by DDGS feeding strategy. There was no effect of DDGS feeding strategy on boneless carcass cutting yields for IC pigs, but these cutting yields were reduced in PC barrows fed the control diets. Belly fat IV was geater in pigs fed 30 percent DDGS diets compared with the control diet, and although bacon slicing yiled was reduced in IC barrows fed none and 305 DDGS diets compared with PC barrows, withdrawing DDGS from the diet before slaughter improved bacon slicing yields of IC barrows.

Most recently, Harris et al. (2017a,b) and Harris et al. (2018) evaluated the effects of different corn DDGS feeding strategies and time intervals between the second Improvest dose and slaughter of IC pigs on growth performance, carcass composition, primal cutout, pork lean quality as well as belly and pork fat quality. Dietary treatments included feeding corn-soybean meal diets (CON), gradual decrease (GD) in dietary DDGS inclusion rate (40, 30, 20, and 10 percent) in phases 1 to 4, respectively, feeding 40 percent DDGS diets in phases 1, 2 and 3, and the removing DDGS from the diet in phase 4 (WD) or feeding 40 percent DDGS during the entire four-phase growing finishing feeding period (NCON). Pigs were admlnisted the second dose of Improvest at nine, seven or five weeks before slaughter.Feed intake of IC pigs fed 40 percent DDGS diets may have been limited by the high fiber content and the age of pigs when the second dose of Improvest was admlnistered, and the withdrawal of DDGS from the diet (WD) before slaughter resulted in a rapid increase in feed intake. Overall, the GD feeding strategy was slightly more effective than the WD feeding strategy in maintaining ADFI, ADG and gain efficiency similar to those fed CON. Using the GD and WD feeding strategies improved carcass dressing percentage and resulted in intermediate carcass primal cut yields and pork loin quality compare with pigs fed CON and NCON feeding strategies. Increasing the time interval of the second Improvest dose before slaughter reduced IV in all carcass fat depots and increased belly thickness, and using the GD and WD feeding strategies also reduced IV in all carcass fat depots.

Effects of Feeding DDGS on Swine Health

There is some evidence that feeding DDGS to swine has beneficial effects on gut health of pigs infected with *Lawsonia intracellularis* (Whitney et al. 2006a,b), but the mechanisms of these effects are unknown because there is limited information on how feeding DDGS may affect the intestinal microbiota of pigs and their susceptibility to infection or colonization with pathogens. Tran et al. (2012) fed diets containing up to 30 percent DDGS to weaned pigs and showed that there was an increase in microbial similarity and a decrease in microbial diversity and richness in the gastrointestinal tract and suggested that these effects may be associated with microbial ecosystem instability. Furthermore, feeding DDGS diets had no effect on serum immunoglobulin concentrations. Rostagno et al. (2013) conducted two experiments to determine if diets containing 20, 30 or 40 percent DDGS affected susceptibility, intestinal levels, and shedding of *Salmonella*. In one of these experiments, pigs infected with *Salmonella* and fed the control diet without DDGS, had higher *Salmonellaa* shedding frequency than pigs fed the 30 percent DDGS diet, but the overall responses suggest that diets containing DDGS did not alter the susceptibility to *Salmonella* colonization in growing-finishing pigs. Saqui-Salces et al. (2017b) showed that feeding diets containing DDGS modulated intestinal cell differentiation by promoting goblet cells and altering expression of nutrient receptors and transporters in growing pigs.

The Porcine Epidemic Diarrhea virus (PEDV) had devastating effects on pig mortality in the U.S. in 2013 and led to extensive investigations to determine its survival, along with other corona viruses (transmissible gastroenteritis virus – TGEV; porcine delta corona virus - PDCoV) in feed and feed ingredients, and the effects of various feed additives on their survival. Dee et al. (2015) showed that PEDV survival in feed varies among types of ingredients and appears to survive the longest in soybean meal, but applying a formaldehyde-based liquid treatment caused virus inactivation in all ingredients. Similarly, Trudeau et al. (2017) evaluated survival of PEDV, TGEV, and PDCoV in various feed ingredients and also showed that PEDV virus survived the longest, and TGEV and PDCoV also had high survival in soybean meal compared to several other ingredients including DDGS. These results suggest that soybean meal is a greater risk factor for transmission of corona viruses via feed than DDGS and other common feed ingredients.

Use of DDGS in Gestation and Lactation Diets

Several recent studies have been conducted to evaluate feeding DDGS to gestating and lactating sows on reproductive and litter performance. Song et al. (2010) fed 0, 10, 20, or 30 percent DDGS diets to mixed-parity lactating sows to determine sow and litter performance, energy and nitrogen digestibility, plasma urea nitrogen and milk fat and protein concentrations. Dietary inclusion rate of DDGS had no effect on DE, ME, nitrogen retention or nitrogen digestibility of the diets. Sows fed the 20 and 30 percent DDGS diets had less plasma urea nitrogen at weaning than sows fed the control diet. No differences were observed for dietary DDGS inclusion rate on sow ADFI and backfat change, but sows fed the 30 percent DDGS diets lost more body weight than sows fed the control diet. Furthermore, preweaning mortality of piglets, litter weight gain and piglet ADG were not affected by dietary DDGS inclusion rate. The results from this study showed that feeding diets containing up to 30 percent DDGS had no effect on sow and litter performance, DE and ME of the diets, nitrogen digestibility, and milk composition compared to feeding a corn-soybean meal control diet, suggesting that feeding up to 30 percent DDGS diets to lactating sows will result in satisfactory sow and litter performance.

Wang et al. (2013) determined the effects of feeding 0, 20, or 40 percent DDGS diets to second and third parity sows during the last 20 days of gestation through a 21 day lactation on sow and litter performance, and colostrum and milk composition. No differences were observed for sow average gestation length, wean-to-estrus interval, sow ADFI, lactation backfat and body weight change regardless of dietary DDGS inclusion rate. Furthermore, there were no effects of dietary DDGS inclusion level on total number of pigs born and born alive, average birth weights, pigs weaned per litter, or piglet ADG during lactation. No differences were observed in total solids, protein, fat and lactose content of milk from sows fed the DDGS diets compared to those fed the corn-soybean meal control diet. These results indicate that sows can be fed diets containing 40 percent DDGS in late gestation and lactation when diets (0.87 percent lysine) are supplemented with 5.2 g lysine/kg to replace all of the soybean meal in the diet, without affecting sow and litter performance or colostrum and milk composition.

Li et al. (2014) evaluated the effects of feeding 0 or 40 percent DDGS diets during gestation and 0 or 20 percent DDGS diets during lactation, when housed in individual stalls or group pens during gestation, on sow and litter performance and sow longevity over three reproductive cycles. Feeding DDGS diets over three reproductive cycles had no effect on sow longevity, but decreased litter size and sow productivity compared to feeding corn-soybean meal diets with no DDGS. However, the detrimental effects of housing sows in group pens during gestation on sow productivity were more evident when fed the corn-soybean meal diets compared to when feeding the DDGS diets.

Greiner et al. (2015) conducted three experiments to evaluate feeding 0 or 10 percent DDGS diets to gestating sows and 0, 10, 20 or 30 percent during lactation (Experiment 1), and 0 or 40 percent DDGS diets during gestation and 20, 30, 40 and 50 percent DDGS diets during lactation (Experiments 2 and 3) on sow and litter performance. The overall results from these studies suggest that feeding 40 to 50 percent DDGS diets to sows during lactation may reduce feed intake and litter performance, but feeding diets containing up to 30 percent DDGS during lactation results in acceptable sow and litter performance.

Corn DDGS has relatively high concentrations of unsaturated fatty acids, which may impact the vitamin E status of piglets and sows fed DDGS. Therefore, Sheltonet al. (2014) conducted a study to determine the α-tocopherol concentration in plasma, milk and pig body tissues when gestating sows were fed 40 percent DDGS diets from breeding to day 69 of gestation and supplemented with 44 or 66 mg/kg DL-α-tocopheryl acetate or 11, 22, 33 or 44 mg/kg D-α-tocopheryl acetate. Supplemental vitamin E was fed from day 70 of gestation through weaning. Results from this study showed that the bioavailability of D-α-tocopheryl acetate relative to DL-α-tocopheryl acetate varies depending on the response crieteria considered, but is greater that the suggested potency value of 1.36.

Song and Shurson (2013) showed that the corn oil in DDGS sources can be peroxidized, which may potentially create oxidative stress when adding at high dietary inclusion rates in sow and pig diets. L-carnitine is important in cell metabolism and regulates mitochondrial transport of long-chain free fatty acids to produce ATP by β-oxidation. Commercial sources of L-carnitine are available, and when supplemented in sow diets and has been shown to improve reproductive performance and milk production, as well as providing antioxidant, anti-inflammatory and other protective functions of the gastrointestinal tract (Ramanau et al., 2004; Ramanau et al., 2005; Musser et al., 2005). Wei et al. (2016) fed 0 or 25 percent DDGS gestation diets and 0 or 40 percent DDGS lactation diets containing 0 or 100 mg/kg L-carnitine in gestation and 0 or 200 mg/kg during lactation. Results of this study showed no effects of feeding DDGS diets to gestating and lactating sows on intestinal barrier functions of their offspring, but supplementing diets with L-carnitine improved intestinal barrier functions of newborn and weaned piglets. The total number of eubacteria in the gastrointestinal tract of weaned pigs was increased by L-carnitine supplementation in the corn-soybean meal diet, but supplemental L-carnitine had no effect when added to the DDGS diet.

Li et al. (2013) determined the effects of feeding 0 or 40 percent DDGS diets during gestation to sows in a group-housed system with electronic sow feeds or individual stalls during gestation on stereotypic and aggressive behaviors. Sows housed in group pens and fed the 40 percent DDGS diet fought for longer periods of time, tended to fight more frequently and had greater salivary cortisol levels (indicator of increased stress) at mixing than sows fed the control corn-soybean meal diet. However, sows housed in individual gestation stalls and fed the 40 percent DDGS diet, spent more time resting, spent less time performing stereotypic behaviors and had lower salivary cortisol concentrations (less stress) compared to sows fed the corn-soybean meal diet with no DDGS. These results suggest that feeding 40 percent DDGS diets may reduce welfare of sows when housed in group pens, but improve welfare of sows when housed in individual gestation stalls.

Conclusions

The extensive amount of research that has been conducted during the past several years has resulted in dramatic improvements in nutritionists ability to effectively use corn DDGS at relatively high diet inclusion rates in precision nutrition feeding programs to reduce feed cost while maintaining acceptable growth, reproduction, carcass and meat quality. Prediction equations have been developed to accurately estimate the ME and SID amino acid content of DDGS sources with variable oil content for swine, as well as for managing diet formulations to achieve desired pork fat quality. By using accurate ME, NE and digestible amino acid and phosphorus values when formulating DDGS for all swine production phases, high diet inclusion rates (up to 30 percent) in all phases of production. In fact, the current trend in the U.S. is to adjust and balance the digestible threonine and branch chain amino acid content of diets containing more than 30 percent DDGS for nursery and growing-finishing pigs diets to achieve equal growth performance and carcass composition compared to feeding conventional corn-soybean meal diets. The reduction in pork fat firmness can be minimized by feeding reduced-oil DDGS sources, withdrawing DDGS from the diet three to four weeks before slaughter, or using the most accurate pork fat quality prediction equations to put formulation constraints in DDGS inclusion rates in markets where pork fat quality is a concern. Evidence also suggests that gestating sows can be fed diets containing up to 50 percent DDGS with no detrimental effects on sow and litter performance if the source is free of mycotoxins, and in doing so, it may improve the welfare of sows housed in individual gestation stalls.

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