CHAPTER 18

Reduced-Oil DDGS in Broiler and Layer Diets

Introduction

CORN DDGS IS AN EXCELLENT FEED INGREDIENT for use in broiler and layer diets. Several scientific reviews have been published that include recommended energy and nutrient values for DDGS when formulating broiler and layer diets (Waldroup et al. 2007; Choi et al., 2008; Swiatkiewicz and Korelski, 2008; Bregendahl, 2008; Salim et al., 2010; El-Hack et al., 2015), but these recommendations generally apply for high-oil (greater than 10 percent crude fat) DDGS and not reduced-oil (less than 10 percent crude fat) DDGS. Fortunately, a considerable amount of research has been conducted during the past seven years to determine the apparent metabolizable energy (AME_n) and digestible amino acid content of DDGS with variable crude fat content. Results from these recent studies are summarized in this chapter. The energy and nutritional composition data, and prediction equations used to derive them, are the most current and representative for corn DDGS sources produced in the U.S., and should be used when formulating precision nutrition DDGS diets for broilers and layers.

Corn DDGS contains about 85 percent of the energy value present in corn for poultry, has moderate levels of digestible essential amino acids, and is high in available phosphorus content. Layer and broiler diets can easily contain up to 10 percent DDGS with minimal, if any, formulation adjustments for energy and amino acids. In a literature review conducted 10 years ago, Swiatkiewicz and Korelski (2008) concluded DDGS is an acceptable ingredient for use in poultry diets and can be safely added at levels of 5 to 8 percent in broiler starter diets, and 12 to 15 percent in grower and finisher diets for broilers and laying hens. However, these are conservative dietary inclusion rates and based on formulating diets on a total amino acid basis rather than a digestible amino acid basis. Recent research studies (Shim et al. 2011; Loar et al., 2010; Masa'deh et al. 2011) have shown DDGS can be added to poultry diets at even higher dietary inclusion rates (e.g. greater than 20 percent) as long as accurate energy and digestible amino acid values are used when formulating DDGS diets.

Energy and Digestible Nutrient Content of Reduced-Oil DDGS for Poultry

Energy is the most expensive component of poultry diets, followed by amino acids and phosphorus. Therefore, determining accurate AME_n, digestible amino acids and available or digestible phosphorus values for the DDGS source being fed to poultry, is the most important aspect for maximizing diet inclusion rates and minimizing diet cost, without affecting performance or meat and egg quality. It is well documented that AME_n, digestible amino acid and available phosphorus content varies among DDGS sources. The most successful poultry integrators around the world use precision nutrition approaches to formulate diets based on AME_n or true metabolizable energy (TME), standardized ileal digestible (SID) amino acids and standardized total tract digestible or available phosphorus. Due to the variability in nutrient composition of DDGS among sources, dynamic estimates of AME and digestible amino acids and phosphorus should be used instead of published reference values, which are outdated. This chapter provides the latest "state-of-the-art" approaches for determining dynamic estimates of AME_n, SID amino acids and available phosphorus using prediction equations. These approaches should be used when determining economic and nutritional value in least-cost feed formulation when evaluating various U.S. corn DDGS sources. Use of these prediction equations will provide accurate estimates of these important diet formulation variables that will enable the use of relatively high dietary inclusion rates of DDGS to achieve substantial diet cost savings, while supporting acceptable growth performance and carcass characteristics in broilers, and egg production and egg quality in layers.

Accurate nutritional values for feed ingredients are also essential for determining economic value, including the highest price that can be paid for DDGS to be used in least cost diet formulations, as well as the maximum diet inclusion rates. Tahir and Pesti (2012b) calculated about $160 million in feed costs can be saved by the global poultry industry if the most accurate digestible amino acid database for feed ingredients is used. Use of linear programming in feed formulation software has been widely implemented to determine the optimal feed ingredient mixture to minimize diet cost by setting restrictions (minimum and maximum inclusion rates) of ingredients relative to meeting nutrient requirements. In addition, most commercial feed formulation software provides the capability of sensitivity analysis or "shadow pricing" to determine the highest price at which an individual ingredient would be included in the formula. Using this approach, feed ingredient usage curves can be developed based on ingredient prices and diet inclusion rates in various feed formulas.

Apparent metabolizable energy (AME_n) content and prediction

The NRC (1994) for poultry indicates the AME_n content of DDGS is 2,667 kcal/kg and the TME_n content is 3,330 kcal/kg on a dry matter (dry matter) basis. However, these estimates are derived from conventional high-oil (greater than 10 percent crude fat) DDGS produced in the ethanol industry over 20 years ago. Today, the composition of reduced-oil DDGS is substantially different than the sources previously used to develop the NRC (1994) energy and nutrient composition values. Three recent studies have been conducted to determine the AME_n content of DDGS sources with variable crude fat concentrations (**Table 1**).

First, the average AME_n value for DDGS reported by Rochell et al. (2011) was 2,678 kcal/kg dry matter, and was similar to the value reported in NRC (1994). However, in the Rochell et al. (2011) study, only one DDGS source contained less than 10 percent crude fat, which corresponded with the lowest AME_n content (**Table 1**). The range in AME_n content among conventional, high-oil DDGS sources was 2,593 to 3,098 kcal/kg dry matter, which was a difference of 505 kcal/kg dry matter among DDGS sources with similar crude fat content. Although only six DDGS sources were evaluated in this study, the AME_n content was not correlated with gross energy (GE), crude fat, crude protein, starch, ash, and ADF content, but it was negatively associated with total dietary fiber (TDF; r = -0.77) and neutral detergent fiber (NDF; r = -0.83) content. This finding indicates fiber content is more closely associated with AME_n content of DDGS than crude fat content.

In a subsequent study, Meloche et al. (2013) evaluated 15 DDGS sources, of which six of these sources contained less than 10 percent crude fat. The average AME_n content of these DDGS sources was 2,309 kcal/kg dry matter, which was 358 kcal/kg dry matter less than the NRC (1994) value (**Table 1**). Furthermore, the difference in AME_n content among these 15 DDGS sources was 955 kcal/kg dry matter, and greater than reported in the Rochell et al. (2011) study. The concentration of AME_n ranged from 1,869 to 2,824 kcal/kg dry matter and was positively correlated with GE (r = 0.69) content, and negatively correlated with TDF (r = - 0.56), NDF (r = - 0.52), acid detergent fiber (ADF; r = - 0.52) content, but was not correlated with crude fat, crude protein, starch, or ash content. These correlations (or lack thereof) are consistent with those reported by Rochell et al. (2011), and indicate fiber content of DDGS is more closely associated with AME_n content than crude fat content. Furthermore, these data also indicate one cannot assume a reduction in crude fat content in DDGS results in an increase in crude protein and fiber content because they were not correlated. Collectively, the results from these two studies indicate crude fat content in DDGS is a very poor predictor of AME_n content.

In a third study, Meloche et al. (2014) reported the average AME_n content of DDGS sources evaluated was 2,764 kcal/kg dry matter, which was 97 kcal/kg dry matter greater than NRC (1994) value for broiler chicks (**Table 1**). When combining data from these three studies, the range in AME_n content among DDGS sources with variable crude fat content was from 1,869 to 3,634 kcal/kg dry matter. This high variability in AME_n content among DDGS sources indicates the use of published book values will not provide reliable AME_n values for use in practical diet formation, and more dynamic approaches are needed. Therefore, Meloche et al. (2013) developed a "best-fit" AME_n prediction equation using chemical composition measures of DDGS:

AME_n kcal/kg dry matter = - 12,282 + (2.60 × GE kcal/kg dry matter) – (40.67 × percent TDF dry matter) + (89.75 × percent Crude Protein dry matter) + (125.80 × percent Starch dry matter) with $R^2 = 0.86$.

Although this equation is highly accurate ($R^2 = 0.86$) in predicting AME_n content of DDGS sources, measurement of gross energy, TDF and starch content is not commonly determined in commercial laboratories. Therefore, these researchers developed an alternative AME_n prediction equation using NDF as the fiber measure instead of TDF:

AME_n kcal/kg dry matter = - 14,322 + (2.69 × GE kcal/kg dry matter) + (117.08 × percent Crude Protein dry matter) + (149.41 × percent Starch dry matter) - (18.30 × percent NDF dry matter) with $R^2 = 0.88$.

This equation resulted in a slight improvement in accuracy ($R^2 = 0.88$) compared with the initial equation, but still requires the determination of gross energy and starch which are often difficult to obtain from analysis provided by commercial laboratories.

Therefore, Meloche et al. (2014) determined the AME_n content of 15 additional DDGS samples that ranged from 5.0 to 14.2 percent crude fat on a dry matter basis, and used these data to validate AME_n prediction equations from Rochell et al. (2011) and Meloche et al. (2013). Although obtaining GE and TDF values from analysis by commercial laboratories is difficult, the best-fit equation with the highest R^2 (0.92) was:

AME_n kcal/kg dry matter = 2,655 - (18.29 × percent NDF) + (44.14 × percent Ether Extract) + (0.21 × GE, kcal/kg) - (10.91 × percent TDF) – (91.08 × percent Ash) with $R^2 = 0.92$ with a prediction accuracy of 321 kcal/kg.

However, if only commonly measured chemical components are available, the following equation can be used, but it has a lower R^2 (0.70), and it is less accurate ($\pm$ 457 kcal/kg) than the previous equation:

Table 1. Gross energy, AMEn, and chemical composition (dry matter basis) of DDGS sources varying in crude fat content (adapted from Rochell et al., 2011; Meloche et al., 2013; and Meloche et al., 2014)									
Rochell et al. (2011)									
DDGS source	**GE, kcal/kg**	**AMEn, kcal/kg**	**Crude fat %**	**Crude protein %**	**TDF %**	**NDF %**	**ADF %**	**Starch %**	**Ash %**
4	5,547	3,098	11.7	29.5	35.9	33.4	8.6	4.9	5.4
1	5,434	2,685	10.2	31.9	35.7	40.1	14.4	6.2	4.5
5	5,375	2,593	10.9	29.7	38.1	40.1	10.6	3.5	4.4
3	5,314	2,628	11.5	29.6	30.3	34.6	11.3	7.9	4.2
6	5,174	2,903	11.5	26.5	32.7	27.7	9.8	3.3	4.5
2	5,076	2,146	3.2	34.7	37.2	51.0	15.8	3.0	5.2
Meloche et al. (2013)									
15	5,167	2,687	13.2	30.6	32.4	34.0	9.9	1.3	5.3
14	5,130	2,824	11.8	32.1	33.5	38.9	13.3	1.1	4.9
12	5,077	2,074	11.3	27.7	37.8	44.0	14.0	1.8	4.4
11	5,075	2,418	11.1	29.7	33.9	36.5	12.1	3.9	4.3
9	5,066	2,273	10.8	29.7	35.3	38.6	13.9	1.6	4.6
10	5,043	2,012	10.8	31.0	35.7	38.9	12.9	0.9	4.9
3	5,022	2,487	6.3	28.9	28.5	27.0	8.2	3.3	5.2
13	5,008	2,032	11.5	26.5	32.7	27.7	9.8	3.3	4.5
2	4,990	2,551	4.2	27.9	30.5	27.3	7.7	3.7	4.8
5	4,963	2,401	9.6	30.1	30.8	33.3	10.5	3.4	4.9
6	4,963	2,526	9.7	29.8	31.3	28.8	10.3	2.8	5.0
7	4,948	2,309	10.0	32.3	33.9	35.9	13.7	1.0	5.3
8	4,938	2,068	10.1	30.3	33.9	38.2	12.5	2.2	5.0
4	4,897	2,103	8.6	32.9	32.5	35.7	13.4	0.8	5.1
1	4,678	1,869	3.2	34.7	37.2	51.0	15.8	3.0	5.2
Meloche et al. (2014)									
1	5,254	3,634	13.3	29.7	31.5	38.3	11.5	2.5	4.8
10	5,254	3,120	14.3	33.0	26.5	32.8	12.1	4.0	4.6
6	5,194	2,535	11.4	29.8	32.1	27.8	8.6	4.7	5.5
15	5,154	3,137	11.6	30.7	33.6	33.0	8.2	6.7	5.0
8	5,148	2,640	8.2	34.1	30.5	37.1	13.2	4.0	5.1
2	5,139	2,553	10.4	32.0	31.6	38.5	12.1	2.3	4.7
11	5,098	3,111	12.0	28.4	28.1	38.1	10.7	10.0	4.6
3	5,061	2,869	9.1	31.6	31.1	39.6	11.6	3.8	5.4
14	5,052	2,644	8.8	28.5	36.6	37.1	9.7	5.9	5.4
4	5,009	2,781	8.0	30.6	32.4	31.0	8.9	4.9	5.6
5	4,978	2,523	7.0	32.2	32.8	31.1	8.6	4.4	5.5
9	4,951	2,461	10.7	32.7	29.2	43.8	14.8	8.1	4.7
13	4,934	1,975	6.1	30.3	31.4	32.9	9.2	4.9	5.4
12	4,884	2,581	5.9	32.3	31.7	34.6	9.4	6.0	5.6
7	4,841	2,903	5.0	34.2	29.3	31.4	8.8	5.6	5.6

AME_n kcal/kg dry matter = 3,673 - (121.35 × percent Crude Fiber) + (55.29 × percent Ether Extract) – (121.08 × percent Ash)

Another approach in addition to using prediction equations to dynamically estimate AME_n content among various DDGS sources in precision poultry nutrition programs, a computer-controlled simulated digestion system to predict the concentration of ME in various feedstuffs for roosters was developed by Zhao et al. (2014), and is being used in the feed industry in China. This method provided accurate predictions of AME and TME content for 17 of the 26 feed ingredients evaluated, including corn DDGS.

Digestible amino acid content and prediction

Selection of accurate total and digestible amino acid databases for feed ingredients is also essential for optimizing bird performance and economic value of feed ingredients. The NRC (1994) for poultry has been widely used for many years, but the energy and nutrient content and digestibility of most ingredients have changed dramatically over the past 23 years, especially for DDGS. Therefore, continued use of feed ingredient energy and nutrient values in this outdated reference is not advised.

Feed formulations based on digestible amino acid content of ingredients have been shown to improve growth rate, feed intake and carcass composition of broilers (Rostagno et al., 1995; Fernandez et al., 1995) compared with formulating on a total amino acid basis. Although many poultry nutritionists assume tamino acid digestibility values obtained from rooster assays are similar among various species of birds (i.e. broilers, layers, ducks, and turkeys), Tahir and Pesti (2012a) showed this assumption is incorrect. These researchers showed digestible amino acid values were 6 to 14 percent greater among 20 feed ingredients evaluated when estimates were derived from the rooster assay compared with values from the same ingredients determined using broiler chick assays.

Ajinomoto Heartland (Chicago, IL) and Evonik Degussa (Hanau-Wolfgang, Germany) have developed comprehensive databases for digestible amino acid content for many feed ingredients fed to poultry. However, the distinguishing difference between these databases is that the Ajinomoto values are derived from rooster assays and Evonik values are based on broiler chick assays. As a result, the digestible lysine (0.60 vs. 0.56 percent), methionine (0.47 vs. 0.44 percent), total sulfur amino acids (TSAA; 1.07 vs. 1.00 percent), and threonine (0.72 vs. 0.71 percent) content of DDGS were greater in the Ajinomoto database than in the Evonik database, respectively. Despite the widespread use of both the rooster and chick assays for determining amino acid digestibility in poultry, the accuracy of using digestibility values from these methods on growth performance of birds of various ages and genetic strains remains to be determined (Tahir and Pesti, 2012b). To provide a better understanding of the economic value of DDGS in broiler, turkey and layer diets, Tahir and Pesti (2012b) conducted a comparison of using Ajinomoto and Evonik digestible amino acid databases in common commercial diet formulations (**Table 2**).

There are several key points to be learned from the comparisons in **Table 2**:

1. Using average feed ingredient prices from 2009, shadow prices for DDGS inclusion in all feed formulations for broilers, turkeys, and layers exceeded the purchase price for DDGS by $65.9 to $139.5/metric ton. This indicates DDGS has much greater value in poultry diets than the market purchase price.

2. Shadow prices of DDGS were greater ($0.2 to $6.4/metric ton) when using the Evonik amino acid digestibility database than the database from Ajinomoto, except for turkey finisher and pre-lay layer diets. This difference was due to the lower digestible amino acid values for DDGS in the Evonik database and emphasizes the importance of choosing accurate amino acid digestibility values when making purchasing decisions for DDGS based on shadow pricing.

3. The value of DDGS is not necessarily greater in high cost diets (i.e. turkey starter) compared with lower-cost diets (i.e. turkey finisher).

4. The value of DDGS varies among classes and ages of birds, with the greatest value in pre-lay layers, and the lowest value in turkey starter diets. The economic value of DDGS is greater for finisher diets for broilers and turkeys than for starter diets.

5. At prices between $221.40 and $226.70/ton, 7 to 17 percent DDGS would be included in broiler starter diets when using the Evonik amino acid digestibility values, but no DDGS would be used at DDGS prices less than $221.40/metric ton if Ajinomoto amino acid digestibility values were used. This further emphasizes the importance of using accurate amino acid digestibility values for DDGS when evaluating its value and use in poultry diets.

6. Even greater diet inclusion rates (20 to 24 percent) of DDGS in broiler starter diets could be used based on economics alone, if DDGS prices were between $211.10 and $191.20/metric ton in this comparison. This indicates greater diet inclusion rates of DDGS can be achieved when the DDGS price decreases relative to the price of other competing ingredients.

7. Broilers in the finisher phase have lower requirements for the dietary concentration of digestible amino acids than during the starter phase. As a result, differences in amino acid digestibility values among databases are

much less important in diets with relatively low digestible amino acid concentrations than in diets containing high digestible amino acid concentrations, which ultimately affect differences in shadow prices and dietary inclusion rates of DDGS.

Many nutritionists assume as crude fat content of DDGS decreases, the crude protein and amino acid content increases. As shown in **Table 3**, this is not a valid assumption because this change in composition does not consistently occur among DDGS sources with variable crude fat content. For example, although total lysine and threonine content tended to increase as crude fat content decreased, tryptophan content decreased and methionine content of the 5.4 percent oil DDGS source was the same as the 10.5 percent oil source (**Table 3**). Apparent ileal amino acid digestibility (AID) for lysine, methionine, threonine and tryptophan was less in reduced-oil DDGS sources compared with the AID 10.5 percent crude fat DDGS source. These results suggest crude fat content of DDGS affects digestibility of some amino acids for poultry (Dozier et al., 2015). However, when considering the combined changes in total concentration and digestibility, there were no differences in apparent ileal digestible lysine, threonine content, small and inconsistent differences in digestible tryptophan content and variable digestible methionine content among these three DDGS sources. These results indicate digestible amino acid content of reduced-oil DDGS sources is not dramatically different than that in high-oil DDGS sources even though digestibility coefficients for several amino acids are reduced. However, methods to dynamically determine digestible amino acid content in DDGS with variable amino acid and crude fat composition are needed.

Table 2. Comparison of DDGS market price versus shadow price in commercial broiler, turkey and layer feed formulations (adapted from Tahir and Peski, 2012b)

		Broiler Starter (Ross)		Broiler Finisher (Cobb)		Turkey Starter (Nicholas)		Turkey Finisher (British United Turkey Males)		Leghorn Prelay (ISA North America)		Leghorn Peak (Hy-Line)	
Ingredient	**$/MT**	**Alin.**	**Evo.**	**Alin.**	**Evo.**	**Alin.**	**Evo.**	**Alin.**	**Evo.**	**Alin.**	**Evo.**	**Alin.**	**Evo.**
Corn	170	58.41	56.17	71.96	71.20	39.48	36.42	81.22	81.17	59.40	59.16	56.08	54.40
Soybean meal	396	36.37	38.23	21.92	22.54	49.85	52.39	14.80	14.80	20.69	21.25	27.98	29.41
Wheat middlings	265	-	-	-	-	-	-	-	-	13.88	13.55	-	-
Poultry grease	487	2.00	2.33	2.70	2.78	5.57	6.03	1.00	1.00	-	-	4.04	4.29
L-lysine	1,666	0.17	0.19	0.18	0.19	0.33	0.35	0.18	0.19	-	-	-	-
DL-methionine	3,721	0.30	0.32	0.19	0.22	0.37	0.40	0.18	0.20	0.15	0.15	0.18	0.21
L-threonine	2,485	0.06	0.08	-	-	0.07	0.09	-	-	-	-	-	-
Limestone	45	0.65	0.65	0.68	0.68	0.73	0.73	0.61	0.61	3.90	3.90	9.08	9.08
Defluorinated phosphate	646	1.70	1.68	2.09	2.08	3.34	3.32	1.41	1.41	1.67	1.66	2.26	2.25
Salt and VTM premix	-	0.36	0.36	0.33	0.33	0.27	0.27	0.67	0.67	0.32	0.32	0.37	0.37
Total diet cost, $/MT		283.5	290.3	249.7	252.6	338.1	347.4	224.6	225.7	241.7	242.8	255.2	260.2
DDGS market price, $/MT	154												
DDGS shadow price, $/MT		221.4	226.7	240.6	240.8	219.9	225.2	236.3	227.6	293.5	291.5	233.8	240.2
Difference between DDGS market price and shadow price, $/MT		67.4	72.7	86.6	86.8	65.9	71.2	82.3	73.6	139.5	137.5	79.8	86.2

Alin.= Ajinomoto, Evo.= Evonik

Table 3. Total, apparent ileal digestibility (AID) and apparent ileal digestible amino acid (AIDAA) content of DDGS sources with different concentrations of crude fat (adapted from Dozier et al., 2015)

Nutrient %	10.5% Oil DDGS			7.9% Oil DDGS			5.4% Oil DDGS		
	Total	AID	AID AA	Total	AID	AID AA	Total	AID	AID AA
Moisture	9.3	-	-	10.6	-	-	10.3	-	-
Crude protein	27.9	-	-	27.6	-	-	29.2	-	-
Arginine	1.25	79.9	1.00	1.35	77.6	1.05	1.32	76.2	1.00
Cysteine	0.55	68.4	0.37	0.57	62.9	0.36	0.52	62.0	0.32
Histidine	0.76	75.0	0.57	0.78	71.2	0.56	0.81	72.1	0.58
Isoleucine	1.05	73.3	0.77	1.05	69.8	0.73	1.13	70.2	0.79
Leucine	3.40	83.5	2.84	3.27	80.1	2.62	3.54	80.3	2.84
Lysine	0.81	55.2	0.45	0.87	51.0	0.44	0.89	50.4	0.45
Methionine	0.55	79.1	0.43	0.64	77.8	0.50	0.54	72.2	0.39
Phenylalanine	1.43	79.9	1.15	1.41	76.7	1.09	1.53	76.8	1.18
Threonine	1.08	61.2	0.66	1.11	56.6	0.63	1.16	56.3	0.65
Tryptophan	0.29	76.7	0.15	0.22	73.3	0.16	0.20	70.8	0.14
Valine	1.43	73.3	1.05	1.45	69.9	1.01	1.52	70.1	1.07

Adedokun et al. (2015) determined the standardized ileal digestibility (SID) of amino acids in five sources of DDGS for broilers (21 days of age, Ross 708) and layers (30 weeks of age, Hy-Line W36). The DDGS sources contained 8.25 to 9.79 percent crude fat, and the ranges in the apparent ileal dry matter and crude protein digestibility, as well as the SID of amino acids in the five DDGS sources are shown in **Table 4**. There was significant variability in digestibility in dry matter, crude, protein and indispensable amino acids among sources with similar crude fat content, with an average of 9.9 percentage points difference in SID amino acid digestibility for layers. As expected, SID lysine coefficients were the most variable (41.3 to 56.5 percent), followed by cysteine (56.8 to 69.0 percent), methionine (67.9 to 78.6 percent), and valine (55.8 to 66.5 percent). Variability of SID of amino acids among the DDGS sources was less for broilers with average difference in coefficients of 7.1 percentage points. Again, the greatest variability in SID coefficients for broilers was for lysine (49.9 to 63.3 percent), followed by isoleucine (67.8 to 76.8 percent), valine (68.5 to 75.9 percent), threonine (61.7 to 69.0 percent), and methionine (77.7 to 85.0 percent). The SID values for lysine and methionine were 8.2 and 7.4 percentage points greater in broilers than layers, respectively. These results suggest different amino acid digestibility coefficients should be used when formulating DDGS diets for layers compared with broilers, and that accurate methods are needed to dynamically estimate SID amino acid content among DDGS sources for poultry. Furthermore, these estimates are the first published SID values for DDGS for layers, and should be used when formulating precision nutrition layer diets.

Because of the high variability in digestible amino acid content among DDGS sources, and the need for methods to dynamically estimate digestible amino acid content, Zhu et al. (2017) conducted a meta-analysis based on 86 observations from 19 publications to develop prediction equations for standardized ileal digestible amino acid values in corn and wheat DDGS for poultry. The overall average chemical composition and coefficient of variation of corn DDGS sources reported in these published studies is shown in **Table 5**. As expected, there is considerable variation in chemical composition among corn DDGS sources which is important for developing robust prediction equations. Lysine content was the most variable among DDGS sources. The standardized ileal digestibility (SID) was greatest for leucine (85.0 percent) and tryptophan (84.5 percent), and the least for lysine (62.7 percent; **Table 6**). The average, range and coefficient of variation in standardized ileal digestible amino acid content in corn DDGS among sources is shown in **Table 7**.

Table 4. Ranges in the apparent ileal dry matter and crude protein digestibility, and SID coefficients (percent) of amino acids in the five corn DDGS sources (adapted from Adedokun et al., 2015)

Nutrient %	Laying hens	Broilers
Dry matter	40.8 – 50.5	42.2 – 51.1
Crude protein	59.6 – 68.3	72.2 – 78.2
Arginine	66.0 – 74.7	76.0 – 82.6
Cysteine	56.8 – 69.0	71.6 – 76.5
Histidine	63.7 – 70.5	70.4 – 75.8
Isoleucine	59.6 – 68.5	67.8 – 76.8
Leucine	72.1 – 80.3	81.8 – 86.0
Lysine	41.3 – 56.5	49.9 – 63.3
Methionine	67.9 – 78.6	77.7 – 85.0
Phenylalanine	71.4 – 78.0	77.2 – 82.5
Threonine	52.8 – 63.8	61.7 – 69.0
Valine	55.8 – 66.5	68.5 – 75.9

Table 5. Chemical composition (percent) of corn distillers dried grains with solubles (DDGS) reported in 19 published studies and used in the prediction of standardized ileal digestible amino acid content (88 percent dry matter basis; adapted from Zhu et al., 2017)

Variable	n	Mean	CV[1] %
Crude protein	59	27.16	11.1
Ash	8	4.66	9.3
Ether extract	24	10.24	27.8
Crude fiber	7	8.10	41.0
Neutral detergent fiber	38	35.66	12.1
Acid detergent fiber	20	9.92	19.4
Essential amino acid			
Arginine	75	1.18	16.5
Cysteine	72	0.50	12.4
Histidine	67	0.70	12.1
Isoleucine	75	1.00	15.9
Leucine	75	3.13	11.5
Lysine	75	0.79	19.9
Methionine	75	0.50	15.8
Phenylalanine	67	1.28	12.5
Threonine	75	1.00	11.2
Tryptophan	51	0.20	19.4
Valine	75	1.33	12.4

[1]Coefficient of variation

Table 6. Average, range, and coefficient of variation in standardized ileal digestibility (SID %) of corn DDGS among sources (adapted from Zhu et al., 2017)

Variable	n	Mean	Minimum	Maximum	CV[1] %
Arginine	75	81.5	53.0	92.6	9.7
Cysteine	67	74.3	49.0	91.9	14.3
Histidine	67	76.3	47.0	89.4	11.4
Isoleucine	75	77.0	52.0	89.4	11.1
Leucine	75	85.0	64.3	93.7	7.3
Lysine	75	62.7	31.3	84.8	19.0
Methionine	75	82.9	53.2	98.4	10.0
Phenylalanine	67	81.6	58.3	91.0	8.3
Threonine	75	70.9	39.2	89.7	12.8
Tryptophan	22	84.5	60.2	92.2	10.7
Valine	75	75.9	48.8	90.6	11.5

[1]Coefficient of variation

Table 7. Average, range, and coefficient of variation in standardized ileal digestible amino acid content in corn DDGS among sources (adapted from Zhu et al., 2017)

Variable	n	Mean	Minimum	Maximum	CV[1] %
Arginine	75	0.96	0.47	1.48	21.1
Cysteine	67	0.37	0.22	0.69	22.0
Histidine	67	0.54	0.29	0.83	19.2
Isoleucine	75	0.77	0.49	1.38	23.1
Leucine	75	2.67	1.90	4.24	15.4
Lysine	75	0.51	0.16	0.84	31.6
Methionine	75	0.42	0.22	0.71	21.7
Phenylalanine	67	1.05	0.70	1.63	17.9
Threonine	75	0.71	0.36	1.10	20.1
Tryptophan	22	0.18	0.08	0.26	26.8
Valine	75	1.02	0.60	1.64	20.6

[1]Coefficient of variation

Total amino acid content was the only chemical component included in standardized ileal amino acid content prediction equations (**Table 8**) because it was the most predictive variable and represented the majority of the variation among sources. The prediction equations developed had low RMSE (0.01 to 0.36) and high R^2, which explained 84 to 99 percent of the variation in values. The prediction model evaluation showed that the slope and intercept, which represent linear bias and mean bias, respectively, were not significantly different from 0 and 1 for all amino acids, indicating that the equations are highly reliable for predicting SID amino acids in DDGS for poultry (**Table 9**). The two most commonly used methods for determining amino acid digestibility of feed ingredients for poultry are the standardized ileal amino acid digestibility chick assay using 3-week old broilers and the precision-fed cecectomized rooster assay. However, the amino acid digestibility estimates obtained from using these assays are different, and some nutritionists prefer using data from one of these assays over the other. Therefore, prediction equations were also developed from data in studies using broiler chick assays and precision-fed cecectomized rooster assays (**Table 10**).

Table 8. Equations to predict standardized ileal digestible amino acid content of sources of DDGS from chemical composition for poultry (adapted from Zhu et al., 2017)

Amino acid	Equation[1]	R^2	RMSE	Prediction Error	Prediction Bias
Arginine	y = -0.20 + 0.96x	0.95	0.13	0.19	0.31
Cysteine	y = -0.07 + 0.88x	0.87	0.09	0.09	0.29
Histidine	y = -0.17 + 1.00x	0.91	0.08	0.10	0.46
Isoleucine	y = -0.01 + 0.77x	0.94	0.12	0.20	0.55
Leucine	y = -0.60 + 1.04x	0.93	0.36	1.48	2.57
Lysine	y = -0.22 + 0.91x	0.87	0.16	0.25	0.25
Methionine	y = -0.12 + 1.05x	0.90	0.08	0.06	0.08
Phenylalanine	y = -0.15 + 0.93x	0.99	0.06	0.22	> 0.001
Threonine	y = -0.17 + 0.88x	0.84	0.24	0.23	0.73
Tryptophan	y = -0.03 + 1.00x	0.99	0.01	> 0.001	0.01
Valine	y = -0.19 + 0.90x	0.93	0.15	0.40	0.82

[1]y is the predicted standardized ileal digestible amino acid content and x is the total concentration of the amino acid in DDGS.

Table 9. Comparison of observed versus predicted standardized ileal digestible amino acid content of sources of DDGS from chemical composition for poultry (adapted from Zhu et al., 2017)

Amino acid %	Observed Mean	Predicted Mean	Intercept	Standard Error	P value
Arginine	0.97	0.97	0.01	0.02	0.75
Cysteine	0.38	0.37	0.00	0.02	0.98
Histidine	0.54	0.53	0.01	0.02	0.59
Isoleucine	0.79	0.79	0.02	0.02	0.50
Leucine	2.58	2.55	0.06	0.08	0.46
Lysine	0.50	0.50	0.01	0.02	0.69
Methionine	0.42	0.42	0.01	0.01	0.54
Phenylalanine	1.09	1.08	0.03	0.03	0.35
Threonine	0.71	0.71	0.01	0.03	0.84
Tryptophan	0.18	0.18	0.00	0.00	0.30
Valine	1.03	1.02	0.03	0.04	0.45

Table 10. Equations to predict standardized ileal digestible amino acid content of sources of DDGS from chemical composition based on broiler chick assays and cecectomized rooster assays (adapted from Zhu et al., 2017)

	Chick assays			Rooster assays		
Amino acid	**Equation[1]**	**R^2**	**RMSE**	**Equation[1]**	**R^2**	**RMSE**
Arginine	y = -0.16 + 0.89x	0.90	0.15	y = -0.09 + 0.95x	0.99	0.03
Cysteine	y = -0.05 + 0.82x	0.79	0.10	y = -0.08 + 0.98x	0.97	0.02
Histidine	y = -0.24 + 1.06x	0.88	0.08	y = -0.08 + 0.95x	0.99	0.04
Isoleucine	y = -0.03 + 0.71x	0.90	0.13	y = -0.11 + 0.95x	0.99	0.04
Leucine	y = -0.79 + 1.08x	0.87	0.37	y = -0.12 + 0.94x	0.98	0.09
Lysine	y = -0.24 + 0.90x	0.73	0.21	y = -0.20 + 0.97x	0.99	0.05
Methionine	y = -0.16 + 1.12x	0.81	0.10	y = -0.05 + 0.97x	0.99	0.01
Phenylalanine	y = -0.19 + 0.95x	0.76	0.27	y = -0.13 + 0.98x	0.98	0.03
Threonine	y = -0.14 + 0.82x	0.82	0.13	y = -0.15 + 0.94x	0.99	0.04
Tryptophan	y = -0.08 + 1.13x	0.99	0.01	y = -0.01 + 0.92x	0.98	0.01
Valine	y = -0.17 + 0.86x	0.86	0.16	y = -0.13 + 0.92x	0.98	0.06

[1]y is the predicted standardized ileal digestible amino acid content and x is the total concentration of the amino acid in DDGS.

Lastly, many commercial feed mills are using near infrared reflectance spectroscopy (NIRS) to quickly and inexpensively obtain nutrient composition data of various feed ingredients to update nutrient composition databases in feed formulation software. Calibrations for total and digestible amino acids in DDGS have been developed for various NIRS equipment. A recent study by Soto et al., (2013) evaluated different strategies for broiler feed formulation when determining amino acid and ME content of feed ingredients. These researchers compared the use of published table values for total amino acids, with total amino acid values obtained from NIRS, digestible amino acid values from NIRS and digestible amino acids and ME values from NIRS in feed formulation and the effects on broiler growth performance and carcass composition. Results from this study showed that using Foss NIRS to determine digestible amino acid and ME content in corn, soybean meal and DDGS, and using these data to formulate diets, resulted in improved body weight gain and feed conversion compared with using total amino acid values from published nutrient composition tables.

Available and digestible phosphorus

Compared with grains and other grain by-products, DDGS contains the greatest concentration of digestible and available phosphorus for poultry. Tahir et al. (2012) reported among multiple samples of corn, soybean meal, bakery by-product meal, wheat, wheat middlings canola meal and wheat shorts, corn DDGS had the lowest phytate and highest non-phytate content among these ingredients. Total phosphorus and phytate content (dry matter basis) of 89 corn DDGS samples averaged 0.96 and 0.26 percent, respectively, which were 124 and 72 percent, respectively, of the values reported in NRC (1994). This indicates that using phosphorus value for DDGS from NRC (1994) will result in underestimation of total phosphorus content and overestimation of phytate and available phosphorus content. These researchers also showed that although phytate phosphorus content of DDGS was positively correlated with Ca concentration, and negatively associated with NDF, ADF, and crude fat content, the development of a best fit regression model resulted in poor prediction (R^2 = 0.37) of phytate content, based on proximate analysis composition of DDGS. As a result, no accurate phosphorus digestibility or availability prediction equations have been developed for DDGS for poultry.

In a recent study by Mutucumarana et al. (2014), the true digestible phosphorus content of corn DDGS was determined to be 0.59 percent, which represented about 73 percent of the total phosphorus (**Table 11**). However, all diets evaluated by Mutucumarana et al. (2014) were deficient in Ca and P, which may have led to an overestimation of phosphorus digestibility because utilization of phytate phosphorus is increased when dietary concentrations of Ca are below the requirement (Mohammed et al., 1991; Tamin and Angel, 2003), and intestinal phytase activity is significantly increased when birds are fed a phosphorus-deficient diet compared with feeding a phosphorus adequate diet (Davies et al., 1970). The results shown in **Table 11** indicate the use on nonphytate phosphorus to estimate digestible phosphorus concentration in feed ingredients is not accurate because the digestible phosphorus content in all ingredients was greater than the nonphytate concentrations, and suggests birds can use a portion of nonphytate P.

Table 11. Phosphorus composition and digestibility of wheat, sorghum, soybean meal, and corn DDGS (adapted from Mutucumarana et al., 2014)

Measure %	Wheat	Sorghum	Soybean meal	Corn DDGS
Total P[1]	0.32 (0.37)	0.24 (0.30)	0.65 (0.62)	0.82 (0.72)
Phytate P	0.21	0.18	0.43	0.38
Nonphytate P[1]	0.11 (0.13)	0.06	0.22 (0.22)	0.44 (0.39)
True digestible P	0.15	0.08	0.52	0.59
As percentage of total P				
Phytate P	66	77	67	47
Nonphytate P	35	23	33	53
True digestible P	46	33	80	73

[1]Values in parentheses are from NRC (1994)

The ability of birds to use phytate phosphorus varies depending on the dietary concentration of Ca, P, vitamin D_3, and fiber, as well as the solubility and location of phytate in the ingredient matrix, feed processing and age of the bird (Ravidran et al., 1995; Angel et al., 2002). Martinez-Amezcua et al. (2006) conducted three experiments to evaluate the effectiveness of adding OptiPhos® phytase and citric acid to broiler diets for improving phosphorus availability in DDGS. In one of the experiments, they used a slope-ratio chick growth and tibia ash assay and determined the bioavailability of phosphorus in DDGS was 67 percent. In another experiment, supplemental phytatse and citric acid released from 0.04 to 0.07 percent more phosphorus from DDGS, which suggests both OptiPhos® phytase and citric acid supplementation can be used to increase the availability of phosphorus in DDGS for poultry. Supplemental phytase and citric acid increased the bioavailability of phosphorus in DDGS from 62 to 72 percent.

Wamsley et al. (2013) determined that the availability of phosphorus in the DDGS source they evaluated was between 66 to 68 percent, which is in agreement with the value reported by Martinez-Amezcua et al. (2006). Therefore, until more accurate methods for estimating phosphorus digestibility and availability are developed for poultry, it is reasonable to assume that about 66 percent of the total phosphorus in DDGS is available to birds.

Feeding Reduced-Oil DDGS to Broilers

Growth performance and carcass characteristics

A total of 17 studies have been published since 2010 evaluating growth performance effects of feeding various diet inclusion rates of DDGS to broilers, and the overall results

Table 12. Summary of growth responses from various dietary DDGS inclusion rates on broiler growth performance

DDGS inclusion rate	Feeding period	DDGS Crude fat	Performance effects	Reference
0, 8, 16, 18, 24, 30% 0, 18, 16, 24%	Finisher I - 28 to 42 d Finisher II - 43 to 56 d	7.4%	Feeding 24 percent DDGS diets during the finisher phases had no effect on ADG, feed intake, and feed conversion	Kim et al., 2016
0, 2.7, 5.4, 8.1% 0, 2, 4, 6 %	Starter - 0 to 28 d Finisher – 29 to 42 d	Not reported	Replacing 20 percent soybean meal (4 to 5.4 percent DDGS) improved body weight gain and reduced diet cost.	Gacche et al., 2016
0, 6, 12%	Starter – 0 to 10 d Grower – 11 to 21 d Finisher – 22 to 42 d	6.5% and 5.4%	No effect on overall ADG, ADFI and Gain:Feed regardless of DDGS oil content and diet inclusion rate.	Cortes-Cuevas et al., 2015

Table 12. Summary of growth responses from various dietary DDGS inclusion rates on broiler growth performance				
DDGS inclusion rate	**Feeding period**	**DDGS Crude fat**	**Performance effects**	**Reference**
0, 5, 10%	0 to 35 d	10.5%	No differences in ADG, ADFI, and Gain:Feed when feeding diets containing 10 percent DDGS from up to 35 d of age.	Hassan and Al Aqil, 2015
0, 15%	Starter - 0 to 21 d Grower - 22-42 d	Not reported	Feeding 15 percent DDGS had no effect on ADG, ADFI, and F/G at d 21 and 42 d.	Min et al., 2015
0, 5, 10, 15%	Starter - 0 to 21 d	8.2%	Feeding the 15 percent DDGS diet decreased ADG on d 7 and 14 compared with feeding 0 and 5 percent DDGS, and decreased on d 21 compared with feeding 0 and 10 percent DDGS. FCR was reduced on d 14 when feeding 15 percent DDGS compared with other inclusion rates, but not on d 21.	Campasino et al., 2015
5, 7, 9% or 8, 10, 12%	Starter - 0 to 13 d Grower - 14 to 26 d Finisher - 27 to 33 d	10.5, 7.8, 5.4%	No effect of crude fat content of DDGS source on growth performance. Adding 5, 7, and 9 percent DDGS resulted in greater ADG, feed intake, and improved feed conversion compared with 8, 10, and 12 percent inclusion rates.	Dozier and Hess, 2015
0 or 12% - starter 0 or 18 % - finisher	Starter – 0 to 21 d Finisher – 21 to 42 d	11.0%	No effect on ADG, ADFI and Gain:Feed when feeding 12 percent DDGS in starter and 18 percent DDGS in finisher when feeding isocaloric and isonitrogenous diets.	Swiatkiewicz et al., 2014
10% 20% 20%	Starter – 0 to 17 d Grower – 17 to 35 d Finisher – 35 to 49 d	11%, 4%	No effect of high or low oil DDGS source on ADG, ADFI, and Gain:Feed in starter and grower. ADFI was greater for birds fed low oil DDGS in the overall feeding period, but no differences in ADG and Gain:Feed.	Kubas and Firman, 2014
7%	Starter - 1 to 21 d Finisher - 22 to 48 d	Not reported	NIRS determined AA content improved BW gain compared with using NRC (1994) values for feed ingredients. Using NIRS to determine digestible AA content improved feed conversion at 21 d compared to using total AA.	Soto et al., 2013
0, 10, 20%	Starter – 0 to 18 d	12.5%, 7.5%, 6.7%t	No effect on BW, feed intake, and feed conversion when fed 20 percent DDGS diets regardless of DDGS oil content	Guney et al., 2013
0, 10, 20%	Starter – 7 to 21 d	Not reported	Increasing DDGS inclusion linearly decreased ADG from d 7 to d 14, but no effects were observed for ADFI and Gain:Feed during this period. There was a quadratic effect on ADFI from d 15 to 21, but no differences in ADG and Gain:Feed.	Perez et al., 2011
0, 10, 20%	Starter – 0 to 21 d Finisher – 22 to 42 d	Not reported	Feeding DDGS increased ADFI but decreased ADG and feed conversion from d 1 to 21, and decreased ADFI, ADG, and feed conversion from d 22 to 42. Feeding 10 percent DDGS vs. 20 percent DDGS had no effect on growth performance during d 1 to 21, but improved ADG and feed conversion during d 22 to 42.	Liu et al., 2011

Table 12. Summary of growth responses from various dietary DDGS inclusion rates on broiler growth performance				
DDGS inclusion rate	**Feeding period**	**DDGS Crude fat**	**Performance effects**	**Reference**
0, 8% 0. 7.5, 15, 22.5, 30%	Starter – 0 to 14 d Grower – 14 to 28 d	Not reported	Feeding 8 percent DDGS during the starter phase, and between 7.5 to 15 percent DDGS during the grower phase provided acceptable growth performance.	Loar et al., 2010
0, 5, 10%	0 to 42 d	12.6%	No effect on overall ADG, ADFI, and feed conversion. Extrusion increased amino acid digestibility in corn DDGS.	Oryschak et al., 2010
0, 10, 20, 30, 40, 50 %	Starter – 0 to 14 d Grower – 14 – 35 d Finisher – 35 to 49 d	Not reported	Up to 20 percent DDGS can be included in broiler diets up to 49 d of age with little or no reduction in growth performance if diets are formulated on a digestible amino acid basis. Adding 30 percent DDGS or more will reduce growth performance.	Wang et al., 2008
0, 15, 30 %	Starter - 0 to 14 d Grower – 15 to 35 d Finisher - 36 to 42 d	9.4%	No effects of feeding 15 percent DDGS continuously and alternating between 0 and 15 percent DDGS on ADG, ADFI, and Gain:Feed when diets are formulated on a digestible amino acids basis. Feeding 30 percent DDGS decreased ADG in each phase and overall ADFI.	Wang et al., 2007

are summarized in **Table 12**. Of these 17 studies, six studies evaluated the effects of feeding reduced-oil DDGS at various inclusion rates to broilers.

Loar et al. (2010) evaluated the effects of adding 0 or 8 percent DDGS to the starter diet (0 to 14 days) and 0, 7.5, 15, 22.5 or 30 percent DDGS to grower diets (14 to 28 days). Feed conversion and mortality rates were not affected by dietary inclusion rate of DDGS, but growth rate was reduced when feeding diets containing more than 15 percent DDGS. However, Shim et al. (2011) fed isonutritional diets containing 0, 8, 16 and 24 percent DDGS using poultry fat as a supplemental energy source, and diets were formulated on a digestible amino acid basis using crystalline amino acids. Body weight gain was improved at the end of the starter phase (d 18) when birds were fed the 8 percent DDGS diet compared with the control diet, and weight gain and gain:feed were similar among dietary DDGS levels at 42 days. Fat pads, breast meat yield and carcass quality were also not different among broilers fed diets containing up to 24 percent DDGS. These results show DDGS can be a good alternative ingredient in diets for broilers at levels up to 24 percent of the diet when diets are formulated on a digestible amino acids basis, without affecting growth performance and carcass or meat quality.

Guney et al. (2013) fed starter and grower diets containing 0, 10 or 20 percent DDGS with variable oil content, and showed no detrimental effects on body weight gain, feed intake, and feed conversion from 0 to 18 days of age (**Table 13**). In fact, feed conversion was improved when feeding the 10 percent DDGS diet using the DDGS source containing the lowest crude fat content.

Kim et al. (2016) determined the effects of feeding diets containing up to 30 percent reduced-oil (7.4 percent crude fat) DDGS on broiler finisher growth performance and carcass composition from 28 to 42 days of age (Finisher 1; **Table 14**) and from 43 to 56 days of age (**Table 15**). During the first finisher phase, there were no differences in body weight gain, feed intake and feed conversion among dietary DDGS inclusion levels except when feeding the 30 percent DDGS diet, which resulted in reduced growth performance. However, there were no differences in carcass weight or carcass fat, fillet, tender and total breast weights among birds fed increasing levels of DDGS in these diets. Similarly during finisher two phase, Kim et al. (2016) showed there were no differences when feeding up to 24 percent reduced-oil DDGS diets on growth performance and carcass composition. Therefore, there is increasing evidence from multiple published studies indicating reduced-oil DDGS can be fed up to 20 percent in starter and grower diets, and up to 24 percent in finisher diets, without affecting growth performance and carcass characteristics. However, diets must be formulated using accurate AME_n and digestible amino acid values for the reduced-oil DDGS sources being fed to achieve acceptable growth performance and carcass characteristics.

Table 13. Effects of adding 0, 10, or 20 percent DDGS containing variable oil content on growth performance of broilers from 0 to 18 days of age (adapted from Guney et al., 2013)

	Control	12.5% Crude Fat DDGS		7.5% Crude Fat DDGS		6.7% Crude Fat DDGS	
Diet inclusion rate	0%	10%	20%	10%	20%	10%	20%
Day 18 body weight, g	596	666	615	607	615	650	598
Day 0-18 feed intake, g/brid/day	53.6	56.0	56.8	54.2	55.9	53.3	56.7
Gain:Feed	1.61	1.51	1.66	1.61	1.63	1.47	1.70

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

Table 14. Effects of feeding increasing diet concentrations of DDGS containing 7.4 percent crude fat to broilers during the Finisher 1 on growth performance and carcass composition (adapted from Kim et al., 2016)

	Dietary DDGS inclusion rate					
Finisher 1, 28 to 42 days of age	**0%**	**6%**	**12%**	**18%**	**24%**	**30%**
Body weight gain, kg	1.60[a]	1.64[a]	1.57[a]	1.56[a]	1.56[a]	1.42[b]
Feed intake, kg	3.01	3.06	3.05	2.97	2.98	3.00
Gain:Feed	1.84[b]	1.87[b]	1.90[b]	1.89[b]	1.90[b]	2.03[a]
Body weight, 43 days of age, kg	2.63	2.70	2.62	2.72	2.58	2.60
Carcass weight, kg	1.92	1.97	1.91	1.98	1.87	1.87
Carcass yield %	73.5[a]	73.2[ab]	73.5[a]	72.9[abc]	72.8[bc]	72.3[c]
Fat, g	27	28	28	28	25	29
Fillet, g	461	481	471	483	458	461
Tender, g	98	100	98	98	96	94
Total breast, g	559	581	569	581	553	554

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

Table 15. Effects of feeding increasing diet concentrations of DDGS containing 7.4 percent crude fat to broilers during the Finisher 2 on growth performance and carcass composition (adapted from Kim et al., 2016)

	Dietary DDGS inclusion rate			
Finisher 2, 43 to 56 days of age	**0%**	**8%**	**16%**	**24%**
Body weight gain, kg	1.45	1.47	1.42	1.44
Feed intake, kg	3.00	3.14	3.02	3.06
Gain:Feed	2.08	2.09	2.07	2.08
Body weight, 57 days of age, kg	4.61	4.67	4.60	4.66
Carcass weight, kg	3.51	3.47	3.49	3.52
Carcass yield %	75.6	75.2	75.7	76.1
Fat, g	79	77	78	80
Fillet, g	976	964	972	988
Tender, g	179	178	180	182
Total breast, g	1,155	1,142	1,152	1,170

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

To obtain a more detailed analysis of the overall effects of feeding diets containing DDGS to broilers, a meta-analysis was conducted to summarize growth performance data from 19 published studies (Martinez-Amezcua et al., 2006; Wang et al., 2007; Wang et al., 2008; Loar et al., 2010; Olukosi et al., 2010; Oryschak et al., 2010; Liu et al., 2011; Min et al., 2011; Barekatin et al., 2013a, b, c; Guney et al., 2013; Wamsley et al., 2013; Swiatkiewicz et al., 2014; Campasino et al., 2015; Cortes-Cuevas et al., 2015: Hassan and Al Aqil, 2015; Min et al., 2015; Kim et al., 2016). The results from this meta-analysis are shown in **Tables 16, 17, and 18**.

Feeding DDGS diets has no effect on body weight gain, improved feed intake by 3 percent, and increased gain:feed by 1.5 percent among the 70 observations reported (**Table 16**). In fact, 73 percent of the observations showed either no change or improved body weight gain, 85 percent of the observations resulted in no change or an improvement in feed intake and gain:feed was unchanged or improved 91 percent of the time (**Table 17**). Feeding DDGS diets during the starter period improved body weight gain and gain:feed compared with feeding DDGS diets during the finisher period and the overall the feeding period (**Table 18**). Increasing DDGS levels linearly increased gain:feed by 5.5 percent when feeding diets containing more than 20 percent DDGS, but had minimal effects when feeding diets containing less than 20 percent DDGS. These results suggest DDGS can be effectively used in starter, grower and finisher broiler diets at inclusion rates up to 20 percent, with minimal effects on body weight gain, feed intake and gain:feed.

Table 16. Summary of effects of dietary DDGS inclusion on growth performance of broilers (summary of 19 studies since 2010)[1]

	DDGS – control (expressed as %)					
Item	**BW[2] gain**	**Feed intake**	**Gain:Feed**	**Initial BW, g**	**Final BW, g**	**Feeding days**
Observations	70	70	70	67	67	70
Studies	16	16	16	15	15	16
Mean	2.7	3.0**	1.5**	345	1,812	26
Minimum	-23.4	-6.5	-21.2	25	302	5
Maximum	76.5	50.8	25.1	3,200	4,660	49

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

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

[2]BW = body weight

Table 17. Summary of growth performance responses from feeding DDGS diets compared with control diets in broilers (summary of 19 studies since 2010).

		Response to dietary corn DDGS[1]		
Item	**N**	**Increased**	**Reduced**	**Not changed**
Body weight gain	70	15	19	36
Feed intake	67	22	10	35
Gain:Feed	70	17	6	47

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

Table 18. Summary of effects of feeding period and diet inclusion rates of corn DDGS on growth performance of broilers (summary of 19 studies since 2010)[1]

Item	Feeding period			SE	DDGS inclusion rate %			SE
	Starter	Finisher	Total		< 10	10 to 20	> 20	
Observations	26	14	30	-	21	34	15	-
Studies	8	3	7	-	9	14	7	-
BW gain[2]	0.56	-5.42	-5.57	2.70	-0.89	-2.57	-6.97	2.85
Feed intake	0.14	-3.31	-0.25	1.73	1.10	-1.64	-2.87	1.95
Gain:Feed[2]	-0.05	1.59	4.17	1.40	-0.38	0.54	5.54	1.55

[1]The least squares means value were reported. The inverse of pooled standard errors of observations was used as a weight factor in the analysis. The starter phase was from 0- 21 days and the finisher phase was from 21 -42 or 49 days. If broilers were fed from 0-42 or 49 days, then growth performance for the entire period was used instead of individual phases.

[2]Every percentage unit (percent) increase in dietary DDGS inclusion resulted in a 0.34 percent decrease (relative percentage) in body weight gain and a 0.32 percent increase in Gain:Feed.

Carcass and meat quality

Researchers have consistently observed positive results in carcass and meat quality when DDGS is added to broiler diets. Corzo et al. (2009) fed diets containing 0 or 8 percent DDGS to broilers and observed no differences in meat color, ultimate pH, cooking loss and shear values. Furthermore, there were no differences in meat texture, but consumer preference of flavor and overall acceptability was slightly greater in meat from broilers fed the control diet. However, consumers characterized chicken breasts from both dietary treatments as "moderately liked," and consumers who "moderately" or "very much" liked the chicken breasts could not differentiate breast meat from birds fed the two dietary treatments. There were no differences in sensory characteristics of chicken breasts between the two dietary treatments, but meat from broilers fed the DDGS diet had increased linoleic and polyunsaturated fatty acid content, which may make it more susceptible to peroxidation during long-term storage of fresh meat. Overall, these researchers indicated that feeding 8 percent DDGS diets resulted in high-quality breast and thigh meat with minimal quality differences.

Schilling et al. (2010) fed diets containing 0, 6, 12, 18 and 24 percent DDGS to broilers for 42 days, and yields of high quality breast meat was achieved regardless of dietary DDGS inclusion rate. Thigh meat quality was similar among birds fed diets containing 0 to 12 percent DDGS, but high dietary inclusion rates resulted in thigh meat that was more susceptible to peroxidation.

Oxidative stress and immune function

There is increasing evidence in multiple animal species that DDGS has chemical properties that reduce oxidative stress and improve immune function and health. Corn DDGS contains relatively high concentrations of tocopherols, tocotrienols and xanthophylls known to be potent antioxidants (see **Chapter 6** in this handbook). Furthermore, corn DDGS contains about 10 percent residual yeast and yeast cell wall components (mannans, α-glucans, and nucleotides) have been shown to have beneficial health effects on animals (Shurson, 2017).

Min et al. (2015) conducted a study to evaluate the effects of feeding 0 or 15 percent DDGS diets to broilers for six weeks under an immunosuppressive challenge (dexamethasone). Birds subjected to the immune challenge had reduced growth rate and feed conversion, but feeding the DDGS diets had no effect on growth performance. Interestingly, feeding the DDGS diets resulted in reduced serum total antioxidant activity as well as serum and liver total superoxide dismutase activity, but increased serum IgA, IgG, and malondialdehyde of 21-day old broilers. Chicks fed DDGS had a greater relative abundance of mRNA encoding IL-4 and IL-6 than birds fed the control diets, and the immune challenge decreased expression of glutathione peroxidase, IL-6, and IL-10. These results suggest some benefit of improving immune function when feeding DDGS to broilers subjected to an immune challenge.

Feeding Reduced-Oil DDGS to Chicken Layers

A total of 11 studies have been published since 2010 evaluating egg production and quality when feeding diets containing various amounts of DDGS to layers, and the overall results of these studies are summarized in **Table 19**. Of these 11 studies, five studies evaluated the effects of feeding reduced-oil DDGS at various inclusion rates to layers.

The use of corn DDGS in chicken layer diets has also recently been reviewed by El-Hack et al. (2015). These authors reported that although previously recommended maximum inclusion rates for DDGS has been 10 to 15 percent in layer diets, several studies have shown much greater inclusion rates can be used to achieve acceptable performance and egg quality if appropriate diet formulation adjustments are made, especially for energy and digestible lysine and methionine content. Furthermore, Masa'deh (2011) showed that feeding 30 percent DDGS diets to laying hens saved $31.15/ton and $28.58/ton for phase I and phase II of production compared to layers fed diets containing no DDGS.

Corn DDGS is an excellent source of energy, digestible amino acids, available phosphorus and xanthophylls for layers. Swiatkiewicz et al. (2014a) indicated feeding diets containing up to 20 percent DDGS without affecting bone quality indices of layers. Furthermore, numerous studies have consistently shown feeding increasing dietary levels of DDGS increases egg yolk color because of the xanthophylls (30 to 56 mg/kg; Trupia et al., 2016) naturally present in corn DDGS.

Table 19. Summary of egg production and egg quality responses from feeding various dietary DDGS inclusion rates to laying hens

DDGS inclusion rate	Feeding period	DDGS Crude fat	Performance effects	Reference
0, 10, 20%	21 to 26 weeks of age	Not reported	No effect on egg production, feed intake, egg weight, and hen body weight change. Feeding 20 percent DDGS reduced daily ammonia emissions 24 percent and hydrogen sulfide emissions by 58 percent.	Wu-Haan et al., 2010
0, 5, 10, 15, 20, 25%	24 to 46 weeks of age (Phase 1) 47 to 76 weeks of age (Phase 2)	10.3%	No effect of dietary DDGS level on feed intake, egg production,Haugh units, specific gravity, and overall weight gain. Increasing DDGS inclusion rate decreased egg weight during Phase 1 but not during Phase 2. Yolk color increased with increasing DDGS in the diets, and decreased nitrogen and phosphorus excretion in manure.	Masa'deh et al., 2011
0, 4, 8, 12, 16%	40 to 50 weeks of age	9.7%	Hens fed DDGS diets had slightly less daily feed intake, but there were no differences in egg production, feed conversion, egg mass, and egg weight amond dietary DDGS inclusion levels.	Tangendjaja and Wina, 2011
0, 17, 35, 50%	54 weeks of age fed for 24 weeks	10.7%	Up to 50 percent DDGS diets can be fed without affecting egg production, feed intake, feed conversion, egg weight, and egg mass as long as adequate digestible amino acids are provided in diets containing DDGS. Feeding DDGS diets improved internal quality of eggs during storage and improved egg yolk color. Haugh unit was highest when feeding the 50 percent DDGS diets but there were no differences in yolk and albumen percentage among dietary treatments.	Sun et al., 2012
10 percent		12.2%	No effect on egg production, feed intake, feed efficiency, initial and final body weight, egg weight, egg mass, egg shell thickness, egg shell breaking strength, Haugh unit, damaged eggs, and marketable eggs.	Deniz et al., 2013a

Table 19. Summary of egg production and egg quality responses from feeding various dietary DDGS inclusion rates to laying hens

DDGS inclusion rate	Feeding period	DDGS Crude fat	Performance effects	Reference
0, 5, 10, 15, 20%	28 to 36 weeks of age	11.2%	No effects of feeding up to 15 percent DDGS diets on egg production, feed intake, feed conversion, egg weight, egg mass, damaged eggs, and marketable eggs, but feeding 20 percent DDGS diets reduced performance and egg weight and mass. No effects of DDGS inclusion rate on egg shell thickness andd egg shell breaking strength, Haugh units, but increased yolk color.	Deniz et al., 2013b
0, 10, 20%	40 to 63 weeks of age	8.3%	No effect on egg production, feed intake, egg weight, and egg mass, and yolk color, egg shell thickness, and feed conversion improved with increasing dietary DDGS level.	Jiang et al., 2013
20%	20 to 33 weeks of age	10.3, 7.3, or 5.2%	Crude fat content of DDGS had no effect on egg production, feed intake, feed conversion, egg weight or mass, and hen weight gain.	Purdum et al., 2014
20%	26 to 39 weeks of age (Phase 1) 40 to 55 weeks of age (Phase 2)	11%	No differences in egg production, feed intake, feed conversion, egg weight and mass, internal egg and egg shell quality within layer phase and overall. Feeding DDGS diets increased egg yolk color.	Swiatkiewicz et al., 2014b
0, 6, 12%	69 to 77 weeks of age	6.5 or 5.4%	No difference in egg production, feed intake, feed conversion, egg weight, and egg mass among dietary treatments. Yolk color was improved in DDGS diets.	Cortes-Cuevas et al., 2015
0, 5, 10, 20%	30 to 42 weeks of age	9%	No effect of dietary DDGS level on egg production, egg weight, egg mass, feed consumption, feed conversion per egg mass, egg specific gravity, haugh units, and egg yolk color. Hens fed the 20 percent DDGS diets had greater body weight loss than other treatments.	Hassan and Al Aqil, 2015

To obtain a more detailed analysis of the overall effects of feeding diets containing DDGS to layers, a meta-analysis was conducted to summarize egg production and quality characteristics using data reported from 17 published studies since 2010 (*Świątkiewicz and Koreleski, 2006;* Shalash et al., 2010; Wu-Haan et al., 2010; Ghazalah et al., 2011; Masa'deh et al., 2011; Tangendjaja and Wina, 2011; Koksal et al., 2012; Sun et al., 2012; Cho et al., 2013; Deniz et al., 2013a; Deniz et al., 2013b; Jiang et al., 2013; Świątkiewicz et al., 2013; Purdum et al., 2014; Cortes-Cuevas et al., 2015; Hassan and Al Aquil, 2015; Trupia et al., 2016).

As shown in **Table 20**, layers fed DDGS diets lost an average of about 16 percent of body weight when fed DDGS diets compared with those fed the control diets, but feed intake, gain:feed, egg production, egg weight, and Haugh units of eggs were minimally (-0.2 to 2.7 percent change relative to control) affected. However, egg shell thickness and yolk color were positively affected (improved by 4.1 and 18.1 percent, respectively) by feeding DDGS diets to layers. The majority of observations reported in these 17 studies showed either an improvement or no change (**Table 21**) in hen body weight change (78 percent), feed intake (78 percent), gain:feed (65 percent), egg production (70 percent), egg weight (75 percent), egg shell thickness (100 percent), yolk color (98 percent), and Haugh units (89 percent).

Body weight change and feed intake were similar for hens fed DDGS diets for more than 16 weeks compared with those fed less DDGS diets for than 16 weeks, but gain:feed was greater (P less than 0.01) in studies where layers were fed diets for less than 16 weeks (**Table 22**). Length of feeding period had no effect on egg production, egg shell thickness and yolk color, but hens fed DDGS diets for less than 16 weeks had a slightly greater (P less than 0.01), but a relatively small (4 percent), reduction in egg weight and a slight improvement (P less than 0.03) in Haugh units compared with layers fed DDGS diets for more than 16 weeks. Increasing diet inclusion rates of DDGS tended (P less than 0.11) to increase body weight change, improved (P less than 0.01) feed intake and increased (P less than 0.01) gain:feed. Furthermore, increasing dietary DDGS inclusion rates decreased (P less than 0.01) egg production and egg weight, but improved (P less than 0.01) Haugh units. Finally, increasing DDGS inclusion rate in laying hen diets tended (P less than 0.11) to improve egg yolk color but slightly reduced egg shell thickness.

Table 20. Summary of effects of feeding corn DDGS diets to laying hens on egg production performance (summary of 17 studies published since 2010)[1]

			DDGS- control (expressed as percent)		
Item	**Observations**	**Studies**	**Mean**	**Minimum**	**Maximum**
Body weight change	36	8	-16.0**	-100.0	183.9
ADFI	65	16	-0.2*	-11.7	6.9
Gain:Feed	51	13	2.7**	-4.0	26.1
Egg production	57	15	-1.7**	-28.7	2.6
Egg weight	69	17	-0.5**	-5.5	3.7
Egg shell thickness	32	9	4.1**	-2.8	8.3
Yolk color	41	11	18.1**	-2.3	58.2
Haugh unit	35	9	-0.1**	-2.4	6.0

**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 were used as a weight factor.

Table 21. Summary of effects of feeding corn DDGS diets to laying hens on egg production performance (summary of 17 studies published since 2010)[1]

		Response to dietary corn DDGS1		
Item	**N**	**Increased**	**Reduced**	**Not changed**
Body weight change	36	1	8	27
ADFI	65	2	14	49
Gain:Feed	51	18	2	31
Egg production	57	5	17	35
Egg weight	69	4	17	48
Egg shell thickness	32	6	0	26
Yolk color	41	33	1	7
Haugh unit	35	0	4	31

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

Table 22. Summary of effects of length of feeding period and dietary inclusion rate of corn DDGS fed to laying hens on egg production performance and egg quality (summary of 17 studies published since 2010)[1]							
	Feeding period			Level of DDGS inclusion %			
Item	**> 16 wk**	**< 16 wk**	**SEM2**	**< 10**	**10 to 20**	**> 20**	**SEM**
Observations	25	44		16	30	23	
Studies	6	11		9	13	12	
BW change	-28.8	-25.6	17.7	-17.2	-17.5	-46.9	4.9
ADFI	0.03	1.0	0.7	-0.4	0.6	1.4	0.3
Gain:Feed	3.6	13.1	2.9	2.2	7.6	15.1	1.0
Egg production	-4.3	-6.6	1.9	-2.2	-5.6	-8.4	0.8
Egg weight	-2.3	-4.3	0.8	-1.3	-3.5	-5.0	0.3
Egg shell thickness	2.0	-0.8	2.0	1.1	1.0	-0.2	0.6
Yolk color	22.3	23.1	5.2	12.5	16.3	39.3	1.9
Haugh unit	1.5	0.1	0.6	-0.1	1.3	1.2	0.2

[1]The inverse of pooled standard errors of observations were used as a weight factor.

SEM = standard error of mean

Egg quality

As summarized in **Table 19**, the majority of recent studies evaluating DDGS inclusion rate and crude fat content reported minimal, if any effects on egg quality at relatively high (greater than 20 percent) DDGS inclusion rates. Sun et al. (2012) fed isocaloric diets containing 0, 17, 35 or 50 percent corn DDGS (10.7 percent crude fat) to 54-week old White Leghorn laying hens for 24 weeks to evaluate egg production and internal egg quality. Egg production, feed intake, feed conversion, egg weight and egg mass were reduced only when feeding the 50 percent DDGS diet during the first 12-week period (**Table 23**). However, once the diets were reformulated to contain increased lysine and methionine content, the reduction in performance from feeding the 50 percent DDGS diet was greatly improved. As a result, there were no differences in egg production, egg weight, and feed intake among dietary treatments during the last six weeks of the study. Feeding increasing dietary levels of DDGS increased egg yolk color and Haugh units, and feeding the 50 percent DDGS resulted in the highest Haugh units indicating eggs produced from hens fed this diet had longer shelf life than eggs from hens fed lower dietary inclusion rates of DDGS (**Table 24**). Furthermore, shell weight percentage and shell breaking strength were greatest for hens fed the 50 percent DDGS diet. These researchers concluded up to 50 percent DDGS can be added to layer diets without affecting egg production, feed intake, feed efficiency, egg weight and egg mass if sufficient amounts of digestible amino acids are present in DDGS diets.

Table 23. Effect of feeding diets containing increasing levels of DDGS to laying hens on egg production performance during a 24-week feeding period (adapted from Sun et al., 2012)				
Measure	**0% DDGS**	**17% DDGS**	**35% DDGS**	**50%DDGS**
Egg production %	87[a]	83[b]	84[a,b]	62[c]
Feed intake, g/hen/day	104.4[a]	104.2[a]	106.0[a]	92.2[b]
Feed efficiency, g egg/kg feed	531.6[a]	487.6[b]	501.9[b]	431.8[c]
Egg weight, g	64.7[a]	63.3[bc]	64.0[ab]	62.6[c]
Egg mass, g/hn/day	56.0[a]	51.8[b]	53.6[ab]	39.1[c]
Body weight change, kg	0.02	0.00	0.00	0.05

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

Table 24. Effect of feeding diets containing increasing levels of DDGS to laying hens on egg quality and composition (adapted from Sun et al., 2012)

Measure	0% DDGS	17% DDGS	35% DDGS	50%DDGS
Yolk color[1]	5.5[d]	7.0[c]	7.9[b]	8.7[a]
Yolk %	26.5	26.8	26.8	26.5
Albumen %	63.7	63.4	63.4	63.3
Shell %	9.8[b]	9.8[b]	9.9[b]	10.1[a]
Haugh unit[2] storage time, weeks				
Week 0	80.5[b]	81.8[b]	82.3[b]	85.3[a]
Week 1	76.4[b]	78.0[b]	78.3[b]	82.3[a]
Week 2	73.7[b]	75.6[b]	76.0[b]	79.9[a]
Week 3	72.4[b]	73.7[b]	74.3[b]	78.2[a]
Shell breaking strength, g	3,924[b]	3,995[b]	3,877[b]	4,299[a]

[a,b,c,d]ry mattereans with different superscripts withing a row are different (P less than 0.05)

[1]Yolk color score ranges from 1 (light) to 10 (dark).

[2]Haugh unit equation = $100 \times \log [\text{height} - 0.01 \times 5.6745 \times (30 \times \text{weight}^{0.37} - 100) + 1.9]$

Using eggs from the same study, Sun et al. (2013) evaluated the effects of feeding isocaloric diets containing 0, 17, 35 or 50 percent corn DDGS (10.7 percent crude fat) to laying hens on egg yolk composition. There were no differences in egg yolk lipid and protein content except when feeding the 50 percent DDGS diet, which resulted in a slight increase in lipid content and a slight decrease in protein content. Moisture content of eggs was not affected by dietary DDGS inclusion rate. However, increasing dietary DDGS content increased total polyunsaturated fatty acid content of egg yolks, and although choline and cholesterol content were initially greater in yolks from hens fed the 50 percent DDGS diet, the concentrations of choline and cholesterol were not different among diets during the last four weeks of the study. As expected, feeding increasing dietary levels of DDGS increased lutein content of egg yolks. However, an interesting finding in this study was that feeding the 50 percent DDGS diet increased the concentration of omega-3 fatty acids (linolenic acid and eicosapentaenoic acid) in egg yolks, which have been shown to have important health benefits for humans.

Trupia et al. (2016) evaluated the effects of feeding diets containing 0, 10 or 20 percent high-oil (13.3 percent crude fat) or reduced-oil (7.4 percent crude fat) DDGS sources on egg production performance and egg quality, and showed no effects on hen weight gain, egg production, feed intake, feed efficiency, egg mass or egg weight among dietary treatments. Specific gravity of eggs was slightly less for hens fed the 10 percent high-oil or 20 percent reduced-oil DDGS diets. However, eggs from hens fed DDGS diets had greater concentrations of tocopherols, tocotrienols, and xanthophylls in egg yolks and increased yellow and red color compared with layers fed the control diet (**Table 25**).

The lipid composition of high-oil and reduced-oil DDGS sources fed in this study is shown in **Table 26**, and indicate the concentrations of tocopherols, tocotrienols and xanthophylls in the DDGS sources fed influenced the composition of these components in egg yolks. In fact, eggs from hens fed the reduced-oil DDGS diet had greater tocopherol content, but lower xanthophyll content than those fed the high-oil DDGS diets. Feeding DDGS slightly altered the fatty acid composition in eggs, but the ratio of saturated to unsaturated fatty acids was similar, with no effect on lecithin or cholesterol content of eggs. These results indicate adding high-oil and reduced-oil DDGS to laying hen diets increases several beneficial lipophilic nutrients in egg yolks and has no apparent detrimental effects on egg yolk quality.

Table 25. Color and lipid composition of egg yolks from laying hens fed 10 or 20 percent high-oil (HO) and reduced-oil (RO) DDGS diets (adapted from Trupia et al., 2016)

Measurement	Control	10% HO DDGS	20% HO DDGS	10% RO DDGS	20%RO DDGS
Yolk L*	58.5[a]	57.8[b]	56.7[c]	57.3[b]	56.6[c]
Yolk a*	-4.3[d]	-3.5[c]	-2.2[a]	-3.5[c]	-2.7[b]
Fatty acid content %					
C16:0	25.5	25.4	25.1	25.5	25.5
C16:1	2.71[a]	2.46[b]	2.08[c]	2.54[ab]	2.49[ab]
C18:0	9.50	9.42	9.56	9.28	9.19
C18:1	45.7[a]	43.5[bc]	42.1[d]	44.4[b]	42.3[cd]
C18:2	13.6[c]	16.4[b]	18.3[a]	15.5[b]	17.6[a]
C18:3	0.44[c]	0.45[d]	0.47[c]	0.45[b]	0.58[a]
C22:0	2.10	2.10	2.20	2.10	2.10
Tocopherols and tocotrienols, µg/g oil					
α-tocopherol	173.8[b]	183.5[ab]	183.3[ab]	209.9[ab]	218.2[a]
β-tocopherol	0.58[c]	0.95[b]	0.96[b]	0.98[b]	1.34[a]
γ-tocopherol	46.0[d]	57.2[cd]	72.2[ab]	67.0[bc]	85.1[a]
δ-tocopherol	1.1[a,b]	1.0[ab]	0.82[b]	1.0[ab]	1.2[a]
α-tocotrienol	2.5[c]	4.0[bc]	5.8[a]	5.1[ab]	6.3[a]
γ-tocotrienol	0.13[b]	0.23[ab]	0.34[a]	0.26[a]	0.32[a]
Total tocotrienols	224.2[c]	246.9[bc]	263.4[abc]	284.2[ab]	312.4[a]
Xanthophylls, µg/g oil					
Lutein	80.0[b]	110.1[a]	123.1[a]	87.4[b]	91.1[b]
Zeaxanthin	22.4[c]	31.7[ab]	36.8[a]	29.1[b]	34.9[a]
β-cryptoxanthin	Not detected	1.1[b]	2.0[a]	1.0[b]	1.7[a]
Unknown	8.6[d]	13.6[bc]	17.3[a]	12.1[c]	14.8[ab]
Total xanthophylls	111.1[d]	156.4[ab]	179.1[a]	129.7[cd]	142.6[bc]

[a,b,c,d]ry mattereans within rows with different superscripts are different (P less than 0.05).

Table 26. Lipid composition of high-oil (13.3 percent) and reduced-oil (7.4 percent) DDGS added to laying hen diets (adapted from Trupia et al., 2016)

Component	13.3% crude fat DDGS	7.4% crude fat DDGS
Fatty acids % of lipid		
C16:0	11.3	11.9
C16:1	0.14	0.13
C18:0	1.73	1.93
C18:1	27.0	27.4
C18:2	57.7	56.3
C18:3	1.50	1.60
Other lipids, mg/kg		
α-tocopherol	20.9	20.1
β-tocopherol	0.45	0.37
γ-tocopherol	76.0	38.3
δ-tocopherol	1.4	0.9
α-tocotrienol	10.9	8.8
γ-tocotrienol	17.4	9.0
δ-tocotrienol	1.40	0.3
Total tocopherols and tocotrienols	128.6	77.8
Lutein	15.7	39.3
Zeaxanthin	9.4	9.7
β-cryptoxanthin	3.3	3.4
Unknown	1.6	3.7
Total xanthophylls	29.9	56.1

Risk of virginiamycin residues in eggs

Small amounts of antibiotics (1 to 2 mg/kg) are often added to fermenters during ethanol and DDGS production to prevent bacterial infections which reduce ethanol yield and result in reduced DDGS quality and nutritional value. The most common antibiotics used in the U.S. ethanol industry are virginiamycin and penicillin. Paulus-Compart (2013) showed the risk of virginiamycin and penicillin residues in DDGS is very low, and if present, they are at such low concentrations they cannot be detected in meat, milk and eggs. Sun et al. (2012) used plate and bio-autography methods to determine the presence of virginiamycin residues in four diets containing 0, 17, 35 or 50 percent DDGS, and found that virginiamycin residues in all diets were below the 0.1 mg/kg restriction limit, and were barely at the 0.05 to 0.1 mg/kg detection limits of these assays. However, the only FDA-approved method for detecting virginiamycin in feed ingredients and eggs is a bioassay. Therefore, the validity of the results reported is questionable. Regardless, these results suggest the possibility of virginiamycin being present in egg yolk, even when DDGS is added at 50 percent to layer diets, is negligible.

Effects of DDGS on molting

Hong et al. (2007) conducted a study to compare feeding a DDGS diet and a non-salt diet to induce molting and compare the effect of feeding-molting and fasting-molting treatments on egg production performance, egg quality and visceral organ weights of laying hens. They used 108 White Leghorn hens (62 weeks of age) with egg production greater than 80 percent and average body weight of 1.08 kg in this study. The dietary treatments consisted of: control (non-molt treatment) feeding-molting treatment (DDGS and non-salt diet) and fasting-molting treatment. Egg production decreased to 0 percent after 18 days in the feeding-molting group, and decreased to 0 percent after 17 days in the DDGS-non-salt feeding-molting group. Egg production stopped for six days in the fasting-molting group. Egg production restarted after 12 and 16 days in the feeding-molting and fasting-molting groups, respectively. Except for egg yolk quality, egg quality was improved for all molting treatments. Liver, heart and oviduct weights of laying hens decreased with all molting treatments. These results indicate that the feeding-molting treatment (DDGS and non-salt diet) could replace the fasting-molting treatment and reduce animal welfare concerns due to fasting during the molting process.

Mejia et al. (2010) fed 36, 45 and 54 grams/day of DDGS in a non-feed withdrawal molting program, compared with feeding similar daily intakes of corn, and found that post-molt egg production (5 to 43 weeks) was greater for hens fed the DDGS molting diets compared to those fed the corn diets. No consistent differences were observed for egg mass, egg specific gravity, feed efficiency or layer feed consumption among the dietary molting treatments for the post-molt period. These researchers concluded that limit feeding corn or DDGS in a non-feed withdrawal program will result in long-term, post-molt performance comparable to ad libitum feeding of a corn-soybean hulls diet.

Wet litter

One of the concerns in managing commercial broiler and layers facilities is minimizing the occurrence of wet litter. Wet litter has been characterized as a consequence of disturbed water balance in birds (Collett, 2012). Many dietary factors can contribute to the occurrence of wet litter including feeding diets containing a high proportion of non-starch polysaccharides, animal protein, saturated free fatty acids, anti-nutritional factors or toxins (Collett, 2012).

High concentrations of sodium, magnesium or sulfate in drinking water and feed are associated with wet litter problems. Maximum acceptable concentrations of sodium (0.05 g/kg, Muirhead, 1995 to 0.25 g/kg, Coetzee, 2005), magnesium (0.125 g/kg, Schwartz, 1994 to 0.25 g/kg, Coetzee, 2005), and sulfate (0.06 g/kg, Keshavarz, 1987 to 0.50 g/kg, Coetzee, 2005) in drinking water for poultry have been reported. Salt is a common contaminant of drinking water around the world, and should be monitored to make appropriate dietary adjustments in supplemental salt content if necessary. Corn DDGS contains variable, and sometimes high sodium (greater than 0.5 percent) and sulfur (greater than 0.6 percent) content which may contribute to wet litter problems if dietary cation-anion difference and supplemental dietary salt levels are not adjusted in diets containing high inclusion rates of DDGS.

Conclusions

Corn DDGS is an excellent feed ingredient for use in broiler and layer diets to reduce feed cost and provide optimal growth performance, egg production, as well as meat and egg quality. The greatest challenge in using DDGS in poultry diets is to use accurate AME_n, digestible amino acid and available phosphorus values for the DDGS source being fed because energy and digestible nutrient content varies among sources. Crude fat content of DDGS is a poor predictor of AME_n and digestible amino acid content. As a result, prediction equations have been developed to accurately estimate actual AME_n and standardized ileal digestible amino acid content of DDGS sources based on chemical composition. As expected, growth responses and carcass composition of broilers among published studies are variable, but the majority of the responses reported showed either no change or an improvement in common production and carcass composition measurements. In fact, recent studies have shown feeding starter broiler diets containing 20 percent reduced-oil DDGS, and finisher diets containing 24 percent reduced-oil DDGS provides acceptable growth performance and carcass quality. Similarly, egg production and egg quality responses of laying hens among published studies are variable, but the majority of the responses reported showed either no change or an improvement in common egg production performance and egg quality measurements. When using accurate AME_n and digestible amino acid values for reduced-oil DDGS in precision nutrition diet formulations for layers, up to 50 percent corn DDGS diets can be fed to layers to achieve acceptable egg production and egg quality.

References

Adedokun, S. A., P. Jaynes, R. L. Payne, and T. J. Applegate. 2015. Standardized ileal amino acid digestibility of corn, corn distillers' dried grains with solubles, wheat middlings and bakery by-products in broilers and laying hens. Poult. Sci. 94:2480–2487.

Angel, R., N.M. Tamim, T.J. Applegate, A.S. Dhandu, and L.E. Ellestad. 2002. Phytic acid chemistry: Influence on phytin phosphorus availability and phytase efficacy. J. Appl. Poult. Res. 11:471-480.

Barekatain, M.R., C. Antipatis, M. Choct, and P.A. Iji. 2013a. Interaction between protease and xylanase in broiler chicken diets containing sorghum distillers' dried grains with solubles. Anim. Feed Sci. Technol. 182:71-81.

Barekatain, M.R., C. Antipatis, N. Rodgers, S.W. Walkden-Brown, P.A. Iji, and M. Choct. 2013b. Evaluation of high dietary inclusion of distillers dried grains with solubles and supplementation of protease and xylanase in the diets of broiler chickens under necrotic enteritis challenge. Poult. Sci. 92:1579-1594.

Barekatain, M.R., M. Choct, and P.A. Iji. 2013c. Xylanase supplementation improves the nutritive value of diets containing high levels of sorghum distillers' dried grains with solubles for broiler chickens. J. Sci. Food. Agric. 93:1552-1559.

Bregendahl, K. 2008. Use of Distillers Co-products in Diets Fed to Poultry. In: Using Distillers Grains in the U.S. and International Livestock and Poultries Industries, B.A. Babcock, D.J. Hayes, and J.D. Lawrence eds., Midwest Agribusiness Trade Research and Information Center, Center for Agricultural and Rural Development, Iowa State University, Ames. Pp. 99-134.

Campasino, A., M. Williams, R. Latham, C.A. Bailey, B. Brown, and J.T. Lee. 2015. Effects of increasing dried distillers' grains with solubles and non-starch polysaccharide degrading enzyme inclusion on growth performance and energy digestibility in broilers. J. Appl. Poult. Res. 00:1-10 http://dx.doi.org/10.3382/japr/pfv018

Cho, J.H., Z.F. Zhang, and I.H. Kim. 2012. Effects of canthaxanthin on egg production, egg quality and egg yolk color in laying hens. J. Agri. Sci. 5:269-274.

Choi, H.S., H.L. Lee, M.H. Shin, C. Jo, S.K. Lee, and B.D. Lee. 2008. Nutritive and economic values of corn distiller's dried grains with solubles in broiler diets. Asian-Australasian J. Anim. Sci. 21(3):414-419.

Coetzee, C.B. 2005. The development of water quality guidelines for poultry in southern Africa. Ph.D. thesis. Animal and Wildlife Sciences, University of Pretoria, South Africa.

Collett, S.R. 2012. Nutrition and wet litter problems in poultry. Anim. Feed Sci. Technol. 173:65-75.

Cortes-Cuevas, A.C., S.R. Estrada, J.A. Menocal, E.A. Gonzalez, and C.L. Coello. 2015. Effect of feeding low-oil DDGS to laying hens and broiler chickens on performance and egg yolk and skin pigmentation. Brazilian J. Poult. Sci. 17:247-254.

Corzo, A., M.W. Schilling, R.E. II. Loar, V. Jackson, S. Kin, and V. Radhakrishnan. 2009. The effects of feeding distillers dried grains with solubles on broiler meat quality. Poult. Sci. 88:432-439.

Davies, M.I., G.M. Ritcey, and I. Motzok. 1970. Intestinal phytase and alkaline phosphatase of chicks: Influence of dietary calcium, inorganic and phytate phosphorus and vitamin D_3. Poult. Sci. 49:1280-1286.

Deniz, G., H. Gencoglu, S.S. Gezen, I.I. Turkmen, A. Orman, and C. Kara. 2013a. Effects of feeding corn distiller's dried grains with solubles with and without enzyme cocktail supplementation to laying hens on performance, egg quality, selected manure parameters and feed cost. Livest. Sci. 15:174-181.

Deniz, G., S.S. Gezen, C. Kara, H. Gencoglu, Y. Meral, and E. Baser. 2013b. Evaluation of nutrient equivalency of microbial phytase in hens in late lay given maize-soybean or distiller's dried grains with solubles (DDGS) diets. Br. Poult. Sci. 54:494-502.

Dozier III, W.A., and J.B. Hess. 2015. Growth and meat yield responses of Hubbard × Cobb 500 male broilers fed diets formulated with distillers dried grains with solubles varying in ether extract content and inclusion rate from 1 to 33 days of age. J. Appl. Poult. Res. 24:436-450.

Dozier III, W.A., K.R. Perryman, and J.B. Hess. 2015. Apparent ileal amino acid digestibility of reduced-oil distillers dried grains with solubles fed to broilers from 23 to 31 days of age. Poult. Sci. 94:379-383.

El-Hack, M.E.A., M. Alagawany, M.R. Farag, and K. Dhama. 2015. Use of maize distiller's dried grains with solubles (DDGS) in laying hen diets: Trends and advances. Asian J. Anim. Vet. Advances 10:690-707.

Fernandez, S.R., Y. Zhang, and C.M. Parsons. 1995. Dietary formulation with cottonseed meal on a total amino acid versus a digestible amino acid basis. Poult. Sci. 74:1168-1179.

Gacche, S.M., A.B. Kanduri, P.V. Patil, and N.Z. Gaikwad. 2016. Extent of replacement of soybean meal with distillers dried grains with solubles (DDGS) on carcass yield, dressing percentage and feed cost in broiler chickens. Anim. Sci. Reporter 10:109-114.

Guney, A.C., M.Y. Shim, A.B. Batal, N.M. Dale, and G.M. Pesti. 2013. Effect of feeding low-oil distillers dried grains with solubles on the performance of broilers. Poult. Sci. 92:2070-2076.

Hassan, S.M., and A.A. Al Aqil. 2015. Effect of adding different dietary levels of distillers dried grains with solubles (DDGS) on productive performance of broiler chicks. Intl. J. Poult. Sci. 14:13-18.

Hong, E.C., J.C. Na, D.C. You, H.K. Kim, W.T. Chung, H.J. Lee, I.H. Kim, and J. Hwangbo. 2007. Effects of feeding non-salt diet on the induced molting in laying hens. Korean J. Poult. Sci. 34:4, 279-286.

Jiang, W., L. Zhang, and A. Shan. 2013. The effect of vitamin E on laying performance and egg quality in laying hens fed corn dried distillers grains with solubles. Poult. Sci. 92:2956-2964.

Keshavarz, K. 1987. Proper water management for poultry. Poult. Dig. (January), pp. 12-22.

Kim, E.J., J.L. Purswell, and S.L. Branton. 2016. Effects of increasing inclusion rates of a low-fat distillers dried grains with solubles (LF-DDGS) in finishing broiler diets. Intl. J. Poult. Sci. 15:182-187.

Kubas, T.A., and J.D. Firman. 2014. Effects of yellow grease addition to broiler rations containing DDGS with different fat contents. Intl. J. Poultr. Sci. 13:437-441.

Liu, N., Y.J. Ru, D.F. Tang, T.S. Xu, and G.G. Partridge. 2011. Effects of corn distillers dried grains with solubles and xylanase on growth performance and digestibility of diet components in broilers. Anim. Feed Sci. Technol. 163:260-266.

Loar, R.E. II, J. S. Moritz, J.R. Donaldson, and A. Corzo. 2010. Effects of feeding distillers dried grains with soluble to broilers from 0 to 28 days posthatch on broiler performance, feed manufacturing efficiency and selected intestinal characteristics. Poult. Sci. 89:2242-2250.

Martinez-Amezcua, C., C.M. Parsons, and D.H. Baker. 2006. Effect of microbial phytase and citric acid on phosphorus bioavailability, apparent metabolizable energy and amino acid digestibility in distillers dried grains with solubles in chicks. Poult. Sci. 85:470-475.

Masa'deh, M.K. 2011. Dried distillers grain with solubles in laying hen and pullet rations. Ph.D. Thesis, Depatment of Animal Science, University of Nebraska-Lincoln.

Masa'deh, M.K., S.E. Purdum, and K.J. Hanford. 2011. Dried distillers grains with soluble in laying hen diets. Poult. Sci. 90:1960-1966.

Mejia, L., E.T. Meyer, P.L. Utterback, C.W. Utterback, C.M. Parsons, and K.W. Koelkebeck. 2010. Evaluation of limit feeding corn and distillers dried grains with soluble in non-feed-withdrawal molt programs for laying hens. Poult. Sci. 89:386392.

Meloche, K.J., B.J. Kerr, N. Billor, G.C. Shurson, and W.A. Dozier III. 2014. Validation of prediction equations for apparent metabolizable energy of corn distillers dried grains with solubles in broiler chicks. Poult. Sci. 93:1428-1439.

Meloche, K.J., B.J. Kerr, G.C. Shurson, and W.A. Dozier III. 2013. Apparent metabolizable energy and prediction equations for reduced-oil corn distillers dried grains with solubles in broiler chicks from 10 to 18 days of age. Poult. Sci. 92:3176-3183.

Min, Y.N. L.L. Li, S.K. Liu, J. Zhang, Y.P. Gao, and F.Z. Liu. 2015. Effects of dietary distillers dried grains with solubles (DDGS) on growth performance, oxidative stress and immune function in broiler chickens. J. Appl. Poult. Res. 24:23-29.

Min, Y.N., F.Z. Liu, A. Karimi, C. Coto, C. Lu, F. Yan, and P.W. Waldroup. 2011. Effect of Rovabio® Max AP on performance, energy and nitrogen digestibility of diets high in distillers dried grains with solubles (DDGS) in broilers. Int. J. Poult. Sci. 10:796-803.

Mohammed, A., M.J. Gibney, and T.G. Taylor. 1991. The effects of dietary levels of inorganic phosphorus, calcium and cholecalciferol on the digestibility of phytate phosphorus by the chick. Br. J. Nutr. 66:251-259.

Muirhead, S. 1995. Good, clean water is critical component of poultry production. Feedstuffs.

Mutucumarana, R.K., V. Ravindran, G. Ravindran, and A.J. Cowieson. 2014. Measurement of true ileal digestibility of phosphorus in some feed ingredients for broiler chickens. J. Anim. Sci 92:5520-5529.

NRC. 1994. Nutrient requirements for poultry. 9th rev. ed. Natl. Acad. Press, Washington, DC.

Olukosi, O.A., A.J. Cowieson, and O. Adeola. 2010. Broiler responses to supplementation of phytase and aDMIxture of carbohydrases and protease in maize–soyabean meal diets with or without maize distiller's dried grain with solubles. Brit. Poult. Sci. 51: 434-443.

Oryschak, M., D. Korver, M. Zuidhof, X. Meng, and E. Beltranena. 2010. Comparative feeding value of extruded and nonextruded wheat and corn distillers dried grains with solubles for broilers. Poult. Sci. 89:2183-2196.

Paulus-Compart, D.M., A.M. Carlson, G.I. Crawford, R.C. Fink, F. Diez-Gonzalez, A. DiCostanzo, and G.C. Shurson. 2013. Presence and biological activity of antibiotics used in fuel ethanol and corn co-product production. J. Anim. Sci. 91:2395-2404.

Perez, V.G., C.M. Jacobs, J. Barnes, M.C. Jenkins, M.S. Kuhlenschmidt, G.C. Fahey Jr., C.M. Parsons, and J.E. Pettigrew. 2011. Effect of corn distillers dried grains with solubles and Eimeria acervulina infection on growth performance and the intestinal microbiota of young chicks. Poult. Sci. 90:958-964.

Purdum, S., K. Hanford, and B. Kreifels. 2014. Short-term effects of lower oil dried distillers grains with solubles in laying hen rations. 93:2592-2595.

Ravindran, V., W.L. Bryden, and E.T. Kornegay. 1995. Phytates: Occurance, bioavailability and implications in poultry nutrition. Poult. Avian Biol. Rev. 6:125-143.

Rochelle, S.J., B.J. Kerr, and W.A. Dozier III. 2011. Energy determination of corn co-products fed to broiler chicks from 15 to 24 days of age, and use of composition analysis to predict nitrogen-corrected apparent metabolizable energy. Poult. Sci. 90:1999-2007.

Rostagno, H.S., J.M.R. Pupa, and M. Pack. 1995. Diet formulation for broilers based on total versus digestible amino acids. J. Appl. Poult. Res. 4:293-299.

Salim, H.M., Z.A. Kruk, and B.D. Lee. 2010. Nutritive value of corn distillers dried grains with soluble as an ingredient of poultry diets: A review. World's Poult. Sci. J. 66:411-432.

Schilling, M.W. V. Battula, R.E. Loar II, V. Jackson, S. Kin, and A. Corzo. 2010. Dietary inclusion level effects of distillers dried grains with solubles on broiler meat quality. Poult. Sci. 89:752-760.

Schwartz, D.L. 1994. Water quality. In: 131st American Veterinary medical Association Annual Convention, San Francisco, CA.

Shalash, S.M.M., S. Abou El-Wafa, R.A. Hassan, Nehad A. Ramadan, Manal S. Mohamed, and Hoda E. El-Gabry. 2010. Evaluation of distillers dried grains with solubles as feed ingredient in laying hen diets. Int. J. Poult. Sci. 9:537-545.

Shim, M.Y., G.M. Pesti, R.I. Bakalli, P.B. Tillman, and R.L. Payne. 2011. Evaluation of DDGS as an alternative ingredient for broiler chickens. Poult. Sci. 90:369-376.

Shurson, G.C. 2017. Review article: Yeast and yeast derivatives in feed additives and ingredients: Sources, characteristics, animal responses and quantification methods. Anim. Feed Sci. Technol. 235:60-76.

Soto, C., E. Avila, J. Arce, F. Rosas, and D. McIntyre. 2013. Evaluation of different strategies for broiler feed formulation using near infrared reflectance spectroscopy as a source of information for determination of amino acids and metabolizable energy. J. Appl. Poult. Res. 22:730-737.

Sun, H., E.J. Lee, H. Samaraweera, M. Persia, and D.U. Ahn. 2013. Effects of increasing concentration of corn distillers dried grains with solubles on chemical composition and nutrient content of egg. Poult. Sci. 92:233-242.

Sun, H., E.J. Lee, H. Samaraweera, M. Persia, H.S. Ragheb, and D.U. Ahn. 2012. Effects of increasing concentrations of corn distillers dried grains with solubles on the egg production and internal quality of eggs. Poult. Sci. 91:3236-3246.

Świątkiewicz, S., A. Arczewska-Wlosek, and D. Jozefiak. 2014a. Bones quality indices in laying hens fed diets with a high level of DDGS and supplemented with selected feed additives. Czech J. Anim. Sci. 59:61-68.

Świątkiewicz, S., A. Arczewska-Wlosek, and D. Jozefiak. 2014b. Feed enzymes, probiotic or chitosan can improve the nutritional efficiency of broiler chicken diets containing a high level of distillers dried grains with solubles. Livest. Sci. 163:110-119.

Świątkiewicz, S., A. Arczewska-Włosek, J. Krawczyk, M. Puchała, and D. Józefiak. 2013. Effects of selected feed additives on the performance of laying hens given a diet rich in maize dried distiller's grains with solubles (DDGS). Brit. Poult. Sci. 54:478-485.

Świątkiewicz, S., and J. Koreleski. 2008. The use of distillers dried grains with solubles (DDGS) in poultry nutrition. World's Poult. Sci. J. 64:257-266.

Świątkiewicz*, S*., and J. Koreleski. 2006. Effect of maize distillers dried grains with solubles and dietary enzyme supplementation on the performance of laying hens. J. Anim. Feed Sci. 15:253-260.

Tahir, M. and G.M. Pesti. 2012a. A comparison of digestible amino acid databases: Relationship between amino acid concentration and digestibility. J. Appl. Poult. Res. 21:1-12.

Tahir, M., and G.M. Pesti. 2012b. Comparison of ingredient usage and formula costs in poultry feeds using different amino acid digestibility databases. J. Appl. Poult. Res. 21:693-705.

Tahir, M., M.Y. Shim, N.E. Ward, C. Smith, E. Foster, A.C. Guney, and G.M. Pesti. 2012. Phytate and other nutrient components of feed ingredients for poultry. Poult. Sci. 91:928-935.

Tamin, N.M., and R. Angel. 2003. Phytate phosphorus hydrolysis as influenced by dietary calcium and micro-mineral source in broiler diets. J. Agric. Food Chem. 51:4687-4693.

Tangendjaja, B., and E. Wina. 2011. Feeding value of low and high protein dried distillers grains and corn gluten meal for layer. Media Peternakan p. 133-139. http://medpet.jouranl.ipb.ac.id/ doi: 10.5398/medpet.2011.34.2.133

Trupia, S., J.K. Winkler-Moser, A.C. Guney, R. Beckstead, and C-Y. O Chen. 2016. Nutritional quality of eggs from hens fed distillers dried grains with solubles. Poult. Sci. 2592-2601.

Waldroup, P.W., Z. Wang, C. Coto, S. Serrate, and F. Yan. 2007. Development of a standardized nutrient matrix for corn distillers dried grains with solubles. Intl. J. Poult. Sci. 6:478-483.

Wamsley, K.G.S., R.E. Loar II, K. Karges, and J.S. Moritz. 2013. The use of practical diets and regression analyses to determine the utilization of lysine and phosphorus in corn distillers dried grains and solubles using Cobb 500 male broilers. J. Appl. Poult. Res. 22:279-297.

Wang, Z., S. Cerrate, C. Coto, F. Yan, and P.W. Waldroup. 2008. Evaluation of high levels of distillers dried grains with solubles (DDGS) in broiler diets. Intl. J. Poult. Sci. 7:990-996.

Wang, Z., S. Cerrate, C. Coto, F. Yan, and P.W. Waldroup. 2007. Effect of rapid and multiple changes in level of distillers dried grains with solubles (DDGS) in broiler diets on performance and carcass characterisitcs. Intl. J. Poult. Sci, 6:725-731.

Wu-Haan, W., W. Powers, R. Angel, and T.L. Applegate. 2010. The use of distillers dried grains plus soluble as a feed ingredient on air emissions and performance from laying hens. Poult. Sci. 89:1355-1359.

Zhao, F., L.Q. Ren, B.M. Mi, H.Z. Tan, J.T. Zhao, H. Li, H.F. Zhang, and Z.Y. Zhang. 2014. Developing a computer-controlled simulated digestion system to predict the concentration of metabolizable energy of feedstuffs for rooster. J. Anim. Sci. 92:1537-1547.

Zhu, J.L., Z.K. Zeng, G.C. Shurson, and P.E. Urriola. 2017. A meta-analysis to predict the concentration of standardized ileal digestible amino acids in distillers dried grains with solubles for poultry. Poult. Sci. (in review)