CHAPTER 6

Nutrient Composition and Variability of Reduced-Oil Corn DDGS Sources

Introduction

ONE OF THE MOST IMPORTANT FACTORS FOR ACHIEVING PRECISION ANIMAL NUTRITION is to accurately determine the energy, nutrient content and digestibility of the feed ingredients being fed. Accurate nutritional values of feed ingredients minimize the risk of over-feeding or under-feeding energy and nutrients relative to the animal's requirement. Accurate nutritional values are also essential for capturing the greatest economic value of feed ingredients by minimizing "safety margins" frequently assigned to target nutrient allowances when formulating animal diets. Furthermore, if nutritionists have confidence in the energy and digestible nutrient values of the sources of feed ingredients they use to formulate animal diets, they are in a better position to increase usage rates of cost competitive feed ingredients, such as DDGS, to obtain greater diet cost savings.

Variation in nutrient content occurs in all feed ingredients. One of the common complaints among DDGS buyers and nutritionists is the nutrient content is too variable compared with other common feed ingredients. While it is well documented that the energy and nutrient content and digestibility is variable among DDGS sources, especially now that the U.S. ethanol industry is partially extracting oil before manufacturing DDGS, it is no more variable than the nutrient content of other feed ingredients. In fact, in a recent feed ingredient analysis survey conducted by Tahir et al. (2012), the coefficient of variation (CV) for crude protein was less among samples of DDGS (5.4 percent) than among samples of corn (8.7 percent) and wheat (19.1 percent; **Table 1**). Furthermore, DDGS has the least variability in NDF and phosphorus content compared with corn, soybean meal, wheat and canola meal. However, as expected, the variability in crude fat content among DDGS sources was the greatest among these feed ingredients because the majority of U.S. ethanol plants are partially extracting variable amounts of corn oil prior to manufacturing DDGS. However, this high variability in crude fat content can be partially attributed to the much greater average crude fat content of DDGS (11.6 percent) compared with the crude fat (0.8 to 3.2 percent) content of the other ingredients used in this comparison.

Table 1. Comparison of nutrient content and variability of common ingredients used in poultry diets, and with poultry NRC (1994) values (dry matter basis; adapted from Tahir et al., 2012)

Item	Corn	Soybean Meal	DDGS	Wheat	Canola Meal
No. samples	133	114	89	22	21
Crude protein %	7.8	52.5	29.1	12.7	41.4
CV %	8.7	3.0	5.4	19.1	2.9
percent of NRC	82	97	99	98	101
Crude fat %	2.9	0.8	11.6	1.2	3.2
CV %	23.9	82.1	11.2	55.0	27.6
percent of NRC	69	72	119	43	79
NDF %	11.0	16.8	42.4	13.4	35.8
CV %	18.3	22.9	9.0	16.4	11.0
Phosphorus %	0.32	0.84	0.96	0.42	0.58
CV %	28.7	7.2	6.5	15.0	43.0
percent of NRC	103	121	124	121	80
Phytate phosphorus %	0.19	0.40	0.26	0.25	0.70
CV %	13.4	5.6	27.2	13.9	4.7
percent of NRC	83	162	72	-	74
Ash %	1.2	6.8	4.8	1.8	7.9
CV %	10.9	4.6	13.9	14.9	9.0

Another key point of this comparison by Tahir et al. (2012) is that the nutrient composition of feed ingredients changes over time, and relying on "static" book values from old published databases can lead to significant over- or underestimation of actual nutrient content of commonly used feed ingredients. This is even more critical for DDGS because the nutrient composition continues to change as ethanol plants adopt new processes to improve ethanol yield, extract more corn oil and enhance protein and amino acid content. Therefore, this chapter provides a summary of the most up to date nutrient composition data on DDGS, and is highly recommended nutritionists rely on these data when assessing value and formulating animal diets containing DDGS.

To manage the variation among DDGS sources, some commercial feed manufacturers have identified specific sources that meet their nutritional specifications and quality standards, and work directly with direct marketers that have the capability of providing identity preserved DDGS sources. Some commercial feed companies also use a preferred suppliers list to help minimize variation in DDGS purchases through third party marketers. Perhaps the best approach is to use the recently developed and validated ME and digestible amino acid prediction equations, based on chemical composition of DDGS sources, to accurately estimate the true nutritional value of the source(s) being used (see **Chapters 19 and 20** of this handbook for more details of prediction equations for swine and poultry).

Nutrient Content and Variability of U.S. Corn DDGS Sources

Several studies have compiled data sets on the nutrient composition of corn DDGS over various time periods (Olukosi and Adebiyi, 2013; Pedersen et al., 2014; Stein et al., 2016, Zeng et al., 2017). However, caution should be used when identifying databases for use in feed formulation because partial oil extraction in the U.S. ethanol industry began in about 2005, and it is widely used in the U.S. ethanol industry today, which has resulted in a high proportion of DDGS sources containing between five to nine percent crude fat. A reduction in oil content not only increases the variability in crude fat content among DDGS sources, but it also changes the profile of other nutrients. However, although many nutritionists and purchasers of DDGS assume crude protein and amino acid content increases as crude fat content decreases in DDGS, this is not always the case. There is often a disproportionate increase in all other chemical components as the crude fat content of DDGS is reduced. Prior to conducting studies on changes in energy and nutrient content of reduced-oil DDGS, the swine NRC (2012) committee, assumed reduced crude fat content in DDGS would reduce the digestible energy (DE), metabolizable energy (ME) and net energy (NE) content for swine and increase the concentrations of other nutrients. Several subsequent research studies have clearly shown that crude fat content is a poor single predictor of DE, ME and NE content for swine (Kerr et al., 2013: 2015) and poultry (Meloche et al., 2013). For more in-depth information, see **Chapters 19 and 20** in the handbook. As a result, NRC (2012) provides estimates of the energy and nutrient profiles of DDGS categorized based on crude fat content. Unfortunately, there were limited data on the ME content and nutrient profiles for medium-oil (n less than 13 for 6 to 9 percent crude fat) and low oil (n less than 2 for less than 4 percent crude fat) DDGS sources. Therefore, these published values do not accurately reflect the variation in nutrient content of the majority of reduced-oil (5 to 9 percent crude fat) DDGS sources currently available from U.S. ethanol plants.

Similar to NRC (2012), a recent review published by Stein et al. (2016) provided nutrient profiles for corn DDGS containing less than 4 percent oil (n less than 3), 5 to 9 percent oil (n less than 15), and greater than 9 percent oil (n less than 100), but this summary is also based on a limited number of samples for DDGS sources containing less than 10 percent crude fat. Because of the poor relationship between crude fat content of DDGS sources and ME content for swine and poultry, prediction equations have been developed and validated (see **Chapters 19 and 22**). It is highly recommended nutritionists use these ME prediction equations to more accurately determine dynamic estimates of the actual energy content of DDGS sources with variable crude fat content.

Another nutrient composition data set for corn DDGS was published by Olukosi and Adebiyi (2013), which included 44 data sets published between 2004 and 2011, and represented 463 samples of corn DDGS (**Table 2**). The majority, but not all, of these samples were produced in the U.S., and because most of the samples were obtained between 1997 and 2010, they do not adequately represent the composition of reduced-oil corn DDGS being produced today. However, their analysis is useful in providing estimates of the variability in nutrient composition among DDGS sources over time, as well as for developing prediction equations to estimate the amino acid content from crude protein content in DDGS. Unfortunately, the accuracy of these prediction equations is not adequate for practical use.

Table 2. Variation in chemical composition of corn DDGS sources from 1997 to 2010 (adapted from Olukosi and Adebiyi, 2013)

Analyte	Average	Minimum	Maximum	SD	CV %
Crude protein %	27.9	23.3	34.7	2.4	8.5
Crude fiber %	7.4	6.2	11.3	1.1	15.1
NDF %	36.6	27.7	51.0	5.8	15.7
ADF %	13.6	8.6	18.5	3.3	24.2
Ether extract %	10.8	3.2	17.7	2.4	22.0
Ash %	4.5	3.1	5.9	0.6	13.6
Calcium %	0.04	0.02	0.08	0.02	53.5
Phosphorus %	0.80	0.69	0.98	0.07	8.8

Pedersen et al. (2014) collected and used near infrared reflectance spectroscopy (NIRS) to analyze 72 corn DDGS samples from 21 different ethanol plants in the U.S. The greatest variation (CV %) in composition among sources was for starch (45 percent), total sugars (19 percent), ether extract (crude fat; 17 percent), and acid hydrolyzed ether extract (13 percent), which exceeded the variability in crude protein, NDF, and ADF content (**Table 3**). These researchers also reported the standard deviation among DDGS sources for each nutritional component which is useful in establishing confidence intervals of expected variation in nutrient profiles.

POET is one of the major ethanol and DDGS producers in the U.S., and owns and operates 27 ethanol plants. Compared with other DDGS sources, POET ethanol plants produce DDGS with the lowest oil content (5.4 percent crude fat) in the market. In a recent survey of the nutrient composition and variability among POET ethanol plants from 2014 to 2016 (Herrick and Breitling, 2016), the nutrient composition of DDGS (dry matter basis) from these plants were: 89.2 $\pm$ 1.13 percent dry matter, 30.7 $\pm$ 1.57 percent crude protein, 5.36 $\pm$ 0.96 percent crude fat, 8.31 $\pm$ 0.82 percent crude fiber, 27.8 $\pm$ 3.27 percent NDF, 10.6 $\pm$ 1.76 percent ADF and 0.92 $\pm$ 0.13 percent sulfur.

Factors that Contribute to Nutrient Content Variability of U.S. Corn DDGS Sources

Many factors contribute to the variability in nutrient content of DDGS beyond partial oil extraction. Olentine (1986) listed a number of variables in the raw materials and processing factors that contribute to variation in nutrient composition of distiller's by-products (**Table 4**). Much of the variation in nutrient content of corn DDGS is likely due to the normal variation among varieties and geographic location where it is grown.

Table 3. Variation in composition of corn DDGS sources based on near infrared reflectance spectroscopy (dry matter basis; adapted from Pedersen et al., 2014)

Analyte	Average	Range	SD	CV %
Moisture %	8.7	6.5 - 12.4	0.8	10
Crude protein %	31.4	27.1 - 36.4	2.1	7
Crude fiber %	7.7	6.4 - 9.5	0.6	7
NDF %	35.1	30.2 - 39.7	2.4	7
ADF %	10.1	8.9 - 11.9	0.6	6
Starch %	6.0	2.9 - 13.9	2.7	45
Total sugars %	9.0	5.4 - 12.6	1.7	19
Ether extract %	9.1	6.5 - 11.8	1.5	17
Acid hydrolyzed ether extract %	11.1	8.4 - 13.5	1.4	13
Ash %	7.1	5.4 - 9.0	0.7	9

Table 4. Factors influencing nutrient composition of distiller's co-products (adapted from Olentine, 1986)	
Raw Materials	**Processing Factors**
Types of grains	Grind Procedure
Grain variety	Fineness Duration
Grain quality Soil conditions Fertilizer Weather Production and harvesting methods	Cooking Amount of water Amount of pre-malt Temperature and time Continuous or batch fermentation Cooling time
Grain formula	Conversion Type, quantity and quality of malt Fungal amylase Time and temperature
	Dilution of converted grains Volume and gallon per bushel or grain bill Quality and quantity of grain products
	Fermentation Yeast quality and quantity Temperature Time Cooling Agitation Acidity and production control Distillation Type: vacuum or atmospheric, continuous or batch Direct or indirect heating Change in volume during distillation Processing Type of screen: stationary, rotating, or vibratory Use of centrifuges Type of presses Evaporators Temperature Number Dryers Time Temperature Type Amount of syrup mixed with grain

The composition of corn has changed over time due to genetic improvements in corn varieties, soil fertilization rates and climatic conditions during the growing season. As shown in **Table 5**, the values for crude fat, crude protein, NDF, ADF, swine DE and poultry TME and AME content in corn are greater than those reported in NRC (2012) for swine and NRC (1994) for poultry (Smith et al., 2015). Therefore, this variability in energy and nutrient composition in corn has direct effects on the nutrient variability among corn DDGS sources. Furthermore, if nutritionists are using energy values for corn from the NRC (1994 and 2012) when formulating poultry and swine diets, they are undervaluing the actual energy content of corn, which has significant economic consequences because energy is the most expensive nutritional component of animal feeds.

The ratio of blending condensed distiller's solubles with the grains fraction to produce DDGS also varies among plants. Because there are substantial differences in nutrient composition between these two fractions, it is understandable the proportion of the grains and solubles blended together will have a significant effect on the final nutrient composition of DDGS. Noll et al. (2006) evaluated the nutrient composition and digestibility of batches of corn DDGS produced with varying levels (0, 30, 60 and 100 percent) of solubles added to the wet grains, which corresponds to adding 0, 12, 25 and 42 gallons of syrup to the grains fraction per minute. Dryer temperatures decreased as the rate of solubles addition to the grains decreased. Particle size increased, and was more variable with increasing additions of solubles to the grains fraction. Adding increasing amounts of solubles resulted in darker colored DDGS (reduced L*) and less yellow color (reduced b*). Increased addition of solubles resulted in increased crude fat, ash, TMEn (poultry), magnesium, sodium, phosphorus, potassium, chloride, and sulfur, but had minimal effects on crude protein and amino acid content and digestibility.

It is also important to remember that nutrient analysis of feed ingredients varies among laboratories, and this has been well documented (Cromwell et al., 1999). As shown in **Table 6**, a single source of DDGS was collected and sent to four different laboratories for analysis using the same analytical procedures, and results were compared. There were differences in dry matter (92.4 to 96.2 percent), crude fat (9.4 to 13.0 percent) and NDF (26.8 to 40.5 percent) among these four laboratories. All laboratory analysis procedures have inherent analytical variation associated with them that can contribute to differences in results, but other factors such as technician error, sampling error, use of outdated reagents and inadequate calibration and maintenance of analytical equipment can contribute to the discrepancies. To help minimize variation in analytical results for DDGS samples among laboratories refer to **Chapter 7** in this handbook for recommended analytical methods for DDGS.

Table 5. Energy and nutrient composition of corn grain sources and comparison with swine NRC (2012) and AME and TME values with poultry NRC (1994; dry matter basis; n = 83 samples; adapted from Smith et al., 2015)

	Swine NRC (2012)	Smith et al. (2015)				
		Average	Range	Difference	SD	CV %
Dry matter %	88.3	86.6	83.7 – 88.9	5.2	1.2	1.4
Crude protein %	9.3	9.5	7.9 – 12.3	4.4	0.98	10.3
Crude fat %	3.9	5.6	3.1 – 10.8	7.7	1.96	35.1
Crude fiber %	2.2	1.7	0.93 – 3.7	2.8	0.42	27.8
NDF %	10.3	10.7	6.7 – 15.4	8.7	2.14	20.0
ADF %	3.3	4.5	1.9 – 8.0	6.1	1.80	39.6
Starch %	70.8	68.5	58.3 – 74.2	15.9	3.4	4.9
Soluble carbohydrates %	-	72.8	63.6 – 79.9	16.3	3.7	5.1
Ash %	1.5	1.4	0.87 – 2.4	1.5	0.28	20.5
GE, kcal/kg	4,454	4,576	4,409 – 4,841	432	101	2.2
DE, kcal/kg (swine)	3,907	4,105	3,904 – 4,344	440	100	2.4
AMEn, kcal/kg	3,764	4,006	3,865 – 4,269	404	94	2.3
TMEn, kcal/kg	3,898	4,086	3,955 – 4,272	317	80	2.0

Table 6. Comparison of nutrient analyses of the same DDGS sample among four laboratories				
	Lab 1	**Lab 2**	**Lab 3**	**Lab 4**
Dry matter %	96.2	95.1	92.4	95.1
Crude protein %	29.6	30.3	30.2	29.3
Crude fat %	9.4	13.0	11.1	11.9
NDF %	32.2	26.8	40.5	27.8
Ash %	4.2	5.0	4.4	4.3

Kerr (2013) unpublished data.

Variation in Indispensable Amino Acid Composition of DDGS Sources

As for all other nutritional components, the amino acid content of DDGS can vary substantially among sources. Olukosi and Abebiyi (2013) summarized several amino acid data sets from several studies published between 1997 and 2010, and the average, minimum and maximum concentrations of all of the indispensable amino acids, along with standard deviations and coefficients of variation are shown in **Table 7**. As previously reported by Fiene et al. (2006), these researchers also showed the correlations between crude protein content and Arg (r = 0.44), Ile (r = 0.26), Lys (r = 0.22), and Trp (r = 0.33) were low and not significant. This means crude protein is a poor indicator of the concentrations of these amino acids in corn DDGS and prediction equations were not developed. Although the concentrations of other indispensable amino acids were significantly correlated with crude protein content (r = 0.68, 0.49, 0.73, 0.81, 0.59 and 0.61 for His, Leu, Met, Phe, Thr, and Val, respectively), they were generally low, and resulting prediction equations had low R^2 values (0.23 to 0.66). These results confirm crude protein content is a poor predictor of amino acid content in corn DDGS, and direct measurement of amino acids is required for accurate determinations.

More recently, Zeng et al. (2017) summarized data sets from 22 peer-reviewed publications and one Master's thesis from studies conducted between 2006 and 2015 (**Table 8**). These data are more reflective of the chemical composition and variability among current corn DDGS sources than those reported by Olukosi and Adebiyi (2013).

Table 7. Variation in indispensable amino acid composition of corn DDGS sources from 1997 to 2010 (adapted from Olukosi and Adebiyi, 2013)					
	Average	**Minimum**	**Maximum**	**SD**	**CV %**
Arg %	1.22	1.06	1.46	0.098	8.0
Cys %	1.73	1.49	1.97	0.057	11.1
His %	0.74	0.65	0.91	0.070	9.4
Ile %	1.07	0.96	1.25	0.072	6.7
Leu %	3.21	2.89	3.62	0.210	6.6
Lys %	0.90	0.62	1.11	0.118	13.1
Met %	0.52	0.44	0.72	0.063	12.0
Phe %	1.29	1.09	1.51	0.123	9.6
Thr %	1.03	0.93	1.16	0.067	6.5
Trp %	0.22	0.16	0.26	0.022	10.3
Val %	1.42	1.30	1.61	0.095	6.7

Table 8. Variation in chemical composition and amino acid content of corn DDGS sources from 2006 to 2015 (88 percent dry matter basis; adapted from Zeng et al., 2017)

Percent	Average	CV %
Crude protein %	27.1	8.7
Crude fiber %	8.2	26.2
NDF %	34.1	13.4
ADF %	11.5	21.2
Ether extract %	8.8	36.3
Ash %	4.1	24.9
Indispensable amino acids		
Arginine %	1.15	11.8
Histidine %	0.74	14.2
Isoleucine %	0.99	11.8
Leucine %	3.16	13.7
Lysine %	0.80	17.9
Methionine %	0.54	15.1
Phenylalanine %	1.32	12.3
Threonine %	1.01	15.5
Tryptophan %	0.20	16.3
Valine %	1.35	11.1

Non-starch Polysaccharide Composition of DDGS Fiber

Knowledge about the non-starch polysaccharide composition of the fiber fraction in DDGS is important when choosing commercially available enzymes to improve energy and nutrient digestibility in DDGS diets fed to swine, poultry and aquaculture. Pedersen et al. (2014) determined the non-starch polysaccharide (NSP) profile of 47 corn and 11 wheat DDGS samples and showed that NSP's represent about 25 to 34 percent of the composition of corn DDGS samples (**Table 9**), and most of it is insoluble. This suggests the fiber fraction in corn DDGS has limited digestibility in the small intestine, and limited fermentability in the lower gastrointestinal tracts of swine, poultry and fish. Cellulose represents about 5 to 9 percent of corn DDGS content, and the predominant non-cellulosic polysaccharides are xylose (7.7 percent) and arabinoxylose (12.3 to 17.2 percent), which are also mainly insoluble. The mannose content in corn DDGS (1.7 percent) is substantially greater than found in corn grain, and is likely due to the mannan content in residual yeast cell walls that are present in DDGS. Corn DDGS has greater arabinose (6.2 percent) and uronic acid (1.6 percent) content than wheat DDGS (5.7 and 0.8 percent, respectively), which results in relatively high arabinose to xylose and uronic acid to xylose ratios. This indicates the fiber (heteroxylan) structure is more complex and variable in corn DDGS compared to wheat DDGS, and therefore, is more difficult to degrade with exogenous enzymes. However, the Klason lignin content, which is indigestible, in wheat DDGS was greater than in corn DDGS samples. Klason lignin is not well defined as a chemical constituent, and may contain protein (Maillard products), residual fat and waxes, and cutin in addition to true lignin. These results suggest the concentrations of substituted xylan and souluble NSP's are altered during DDGS production from their original structure in corn grain.

Table 9. Average concentration (%) and variation in the nutrient and non-starch polysaccharide (NSP) composition of 47 corn and 11 wheat DDGS samples (dry matter basis; adapted from Pedersen et al., 2014)

	Corn DDGS				Wheat DDGS			
	Mean	**Range**	**SD**	**CV %**	**Mean**	**Range**	**SD**	**CV %**
Moisture	8.7	6.5 – 12.4	0.8	10	7.6	6.8 – 8.7	2.0	2
Crude protein	31.4	27.1 – 36.4	2.1	7	33.4	30.3 – 37.9	2.8	9
Ether extract	9.1	6.5 – 11.8	1.5	17	5.2	4.4 – 6.5	0.8	16
Acid hydrolyzed ether extract	11.1	8.4 – 13.5	1.4	13	7.3	6.5 – 8.8	0.8	11
NDF	35.1	30.2 – 39.7	2.4	7	30.6	27.3 – 34.2	2.6	8
ADF	10.1	8.9 – 11.9	0.6	6	10.5	9.5 – 12.2	0.8	7
Crude fiber	7.7	6.4 – 9.5	0.6	7	6.7	5.5 – 8.8	0.9	14
Starch	6.0	2.9 – 13.9	2.7	45	4.0	< 1.0 – 8.8	4.2	103
Total sugars	9.0	5.4 -12.6	1.7	19	9.8	4.6 – 12.4	2.2	23
Ash	7.1	5.4 – 9.0	0.7	9	9.1	8.1 – 10.0	0.4	5
Total NSP	28.3	25.0 - 33.7	2.0	9	26.2	24.2 – 29.1	0.9	4
Soluble NSP	3.1	1.6 - 6.5	0.8	47	6.7	5.3 – 8.0	0.1	2
Cellulose	6.7	5.2 - 9.1	0.8	16	5.0	3.5 – 6.7	1.6	32
Non-cellulosic polysaccharides								
Total xylose	7.7	6.7 - 10.0	0.7	10	8.6	7.0 – 9.3	0.7	8
Soluble xylose	0.6	0.1 - 1.6	0.3	62	2.3	1.5 – 3.2	0.5	22
Total arabinose	6.2	5.6 - 7.2	0.4	7	5.7	5.1 – 6.2	0.0	0
Soluble arabinose	0.7	0.2 - 1.5	0.3	45	1.7	1.2 – 2.2	0.3	15
Total glucose	2.8	2.1 - 4.4	0.4	13	3.3	2.7 – 3.7	0.1	5
Soluble glucose	0.3	0.0 - 1.6	0.4	190	1.1	0.1 – 2.1	1.0	89
Total mannose	1.7	1.2 - 2.0	0.2	12	1.6	1.3 – 1.8	0.2	13
Soluble mannose	0.6	0.4 - 0.9	0.1	19	0.7	0.4 – 0.8	0.1	18
Total galactose	1.5	1.3 - 2.1	0.2	11	1.1	1.0 – 1.2	0.1	11
Soluble galactose	0.3	0.2 - 0.5	0.1	29	0.6	0.4 – 0.7	0.1	18
Total uronic acids	1.6	1.4 - 2.0	0.1	8	0.8	0.7 – 0.9	0.1	12
Soluble uronic acids	0.5	0.3 - 0.6	0.1	11	0.3	0.2 – 0.4	0.0	15
Klason lignin	2.5	1.5 - 4.7	0.7	26	6.6	4.4 – 9.3	2.1	32
Arabinose: Xylose	0.80	0.71 - 0.85	0.0	5	0.66	0.62 – 0.70	0.01	9
Uronic acid: Xylose	0.20	0.16 - 0.23	0.0	8	0.09	0.08 – 0.11	0.0	21

Fatty Acid Composition and Peroxidation Indicators of Corn Oil in DDGS

The fatty acid composition of DDGS is important for several reasons including its contribution to ME and NE values, potential impacts on milk fat concentrations in dairy cattle, effects on pork fat firmness in growing-finishing pigs, and susceptibility to lipid peroxidation during production, transport and storage. As shown in **Table 10**, the major fatty acids present in DDGS corn oil are linoleic acid (54 percent), oleic acid (26 percent), and palmitic acid (14 percent), of which linoleic and oleic acids are unsaturated fatty acids that contribute to the high energy content of DDGS, but also cause the oil in DDGS to be susceptible to peroxidation. Furthermore, the fatty acid profile does not appreciably differ between high-oil (greater than 10 percent crude fat) and reduced-oil (less than 10 percent crude fat) DDGS sources. Although there is no detectable eicosapentaenoic acid (EPA) concentrations in DDGS oil, there are small amounts of docohexaenoic acid (DHA) present, which is a physiologically important omega-3 fatty acid for neural, retinal and immune functions. There are minimal average differences in the indicators of lipid peroxidation (free fatty acid content, thiobarbituric acid and peroxide value) among high- and reduced oil DDGS sources, but considerable variation in these measures.

For a more comprehensive analysis of lipid peroxidation among DDGS sources, Song and Shurson (2013) analyzed corn oil extracted from 31 corn DDGS sources, and compared these data with a corn grain reference sample (**Table 11**). The correlations between Minolta L* and b* and peroxide value were - 0.63 and – 0.57, respectively, and greater for TBARS (r = - 0.73 and -0.67, respectively). These significant negative correlations between color measurements and peroxidation measurements of DDGS suggest color may be a useful general indicator of the extent of lipid peroxidation in DDGS sources because brown-colored oxypolymers are produced during the polymerization reactions during lipid peroxidation (Buttkus, 1975; Khayat and Schwall, 1983). However, when Song et al. (2013) fed 30 percent DDGS diets containing the most peroxidized source of DDGS from this study (which also contained

Table 10. Fatty acid composition and extent of lipid peroxidation in DDGS sources with variable crude fat content (adapted from Kerr et al., 2013).

	Average of DDGS sources (>10 % crude fat)	Range	Average of DDGS sources (>10 % crude fat)	Range
No. samples	8		7	
Ether extract %	11.2	10.1 -13.2	8.0	4.9 -10.0
Fatty acid % of total oil				
Myristic, 14:0	0.07	0.06 - 0.08	0.04	ND - 0.08
Palmitic, 16:0	14.2	13.6 - 15.4	14.2	14.0 - 14.6
Palmitoleic, 16:1	0.14	0.12 - 0.16	0.12	ND - 0.15
Stearic, 18:0	2.2	2.0 - 2.6	2.2	2.1 - 2.3
Oleic, 18:1	26.0	24.8 - 27.3	26.2	25.2 - 27.2
Linoleic, 18:2	54.0	51.9 - 55.0	53.9	53.4 - 54.5
Linolenic, 18:3	1.6	1.4 - 1.8	1.6	1.6 - 1.8
Arachidonic, 20:4	ND	ND	ND	ND
Eicosapentaenoic, 20:5	ND	ND	ND	ND
Docosapentaenoic, 22:5	ND	ND	ND	ND
Docosahexaenoic, 22:6	0.18	0.15 - 0.27	0.21	0.16 - 0.26
Lipid peroxidation				
Free fatty acids %	1.7	1.1 - 2.4	1.1	0.6 - 1.7
Thiobarbituric acid absorbance	7.8	5.7 - 11.8	10.6	5.3 - 17.1
Peroxide value, mEq/kg	5.4	0.2 - 19.0	7.7	0.6 - 17.5

Table 11. Measurements of lipid peroxidation in oil extracted from corn dried distillers grains with solubles (DDGS) and DDGS color (adapted from Song and Shurson, 2013)

		DDGS				
	Corn	**Average**	**Median**	**Minimum**	**Maximum**	**CV %**
Peroxide value, mEq/kg oil	3.1	13.9	11.7	4.2	84.1	97.5
TBARS, ng MDA equivalents/mg oil	0.2	1.9	1.7	1.0	5.2	43.6
Color						
L*	83.9	54.1	54.9	45.2	58.1	4.6
a*	2.6	10.9	10.8	9.3	12.4	7.2
b*	20.0	37.3	37.5	26.6	42.7	8.8

0.95 percent sulfur), they observed no negative effects on growth performance of weaned pigs. The lack of a growth performance response was attributed to an increase in sulfur-containing antioxidant compounds resulting from feeding DDGS, and additional supplemental vitamin E was not necessary to prevent a reduction in growth performance. Similar results were also observed by Hanson et al. (2015) when feeding a highly peroxidized DDGS source to weaned pigs. These results suggest that although significant lipid peroxidation occurs in DDGS, it does not appear to negatively affect growth performance and health of weaned pigs. It is possible the relatively high natural antioxidants found in DDGS are sufficient to overcome potential negative effects of feeding peroxidized oil in DDGS to pigs.

Natural Antioxidant and Phytochemical Composition of DDGS

While the primary role of feed ingredients is to provide sufficient amounts of energy and digestible nutrients to meet the requirements of animals, some feed ingredients also contain compounds that provide additional physiological benefits beyond the nutrients they provide to the diet. These compounds are sometimes described as having "functional" or nutraceutical properties (i.e nutritional and pharmaceutical). There are several bioactive compounds in corn that provide health benefits including vitamin E, ferulic acid and carotenoids. These compounds, along with others, may collectively contribute to the antioxidant capacity and potential health benefits of DDGS.

Data on phytochemical content and antioxidant capacity of DDGS are limited. However, quantifying these phytochemical components is important to begin understanding the beneficial effects on gut health and immune system responses observed from feeding DDGS diets to pigs, poultry and fish. Initial evidence suggests DDGS contains significant amounts of various antioxidant compounds that may provide health benefits while preventing oxidative stress from feeding peroxidized oil in some DDGS sources to animals. The first study to quantify various natural antioxidants and phytochemicals in DDGS was conducted by Winkler-Moser and Breyer in 2011. These researchers obtained a sample of DDGS from POET and conducted an extensive analysis to determine the fatty acid profile, tocopherols, tocotrienols, carotenoids, oxidative stability index (OSI) and phytosterols in oil extracted from DDGS (**Table 12**). Tocopherols are the predominant antioxidants present in oils (Kamal-Eldin, 2006), and are important in minimizing peroxidation under pro-oxidant conditions. Tocotrienols also serve as antioxidants (Schroeder et al., 2006), and appear to contribute to reducing blood cholesterol, preventing cancer and protecting the neural system (Sen et al., 2000). The major carotenoids in corn oil are lutein and zeaxanthin, which have been shown to protect against age-induced macular degeneration and cataracts in humans (Zhao et al., 2006). Beta-carotene and beta-cryptoxanthin are precursors to vitamin A (Bendich and Olson, 1989), and all carotenoids have been shown to have beneficial health effects beyond providing vitamin A activity to diets, including antioxidant activity, improved immune response, and protection against several types of cancer (Bendich and Olson, 1989; Rao and Rao, 2007). Phytosterols are valuable constituents in functional foods because of their ability to reduce blood cholesterol and block cholesterol re-absorption from the lower gastrointestinal tract (Gylling and Miettinen, 2005). Steryl ferulates assist in the cholesterol reducing properties of phytosterols (Rong et al., 1997) and also have antioxidant activity (Nyström et al., 2005). In a more recent study, Shim et al. (personal communication) determined the antioxidant capacity, and tocopherol, tocotrienol, xanthophylls and ferulic acid content and variability among 16 sources of DDGS and compared these values with a corn sample (**Table 13**). Results from this study showed there is substantial variability in concentrations of these compounds among DDGS sources, but DDGS contains two- to three-fold greater concentrations than found in corn.

Table 12. Fatty acid profile, natural antioxidant compounds, oxidative stability and phytosterols in oil extracted from DDGS (adapted from Winkler-Moser and Breyer, 2011)

Analyte	Concentration
Free fatty acids % oleic acid	10.5 + 0.18
Fatty acids (percent of oil)	
16:0	12.9
16:1	0.1
18:0	1.8
18:1	28.1
18:2	55.5
20:0	0.3
18:3	1.2
20:1	0.0
Calculated iodine value	123.1
Total tocopherols, µg/g	1,104
Alpha-tocopherol, µg/g	296
Gamma-tocopherol, µg/g	761
Delta-tocopherol, µg/g	48
Total tocotrienols, µg/g	1,762
Alpha-tocotrienol, µg/g	472
Gamma-tocotrienol, µg/g	1,210
Delta-tocotrienol, µg/g	80
Total carotenoids, µg/g	75
Lutein, µg/g	47
Zeaxanthin, µg/g	24
Beta-cryptoxanthin	3.3
Beta-carotene, µg/g	0.9
OSI, hours at 110°C	6.62
Total phytosterols, mg/g	21.7
Campesterol, mg/g	2.97
Campestanol, mg/g	1.35
Stigmasterol, mg/g	1.10
Sitosterol, mg/g	10.3
Sitostanol, mg/g	3.72
Avenasterol, mg/g	0.93
Cycloartenol, mg/g	0.71
24-Methylene cycloartanol, mg/g	0.30
Citrostadienol, mg/g	0.31
Steryl ferulates, mg/g	3.42

Table 13. Antioxidant capacity, tocopherols, tocotrienols, xanthophylls and ferulic acid content (dry matter basis) of 16 sources of DDGS compared with corn (adapted from Shurson, 2017)

	Corn	DDGS		
		Average	Minimum	Maximum
Antioxidant capacity, mmol tocopherol equiv./kg	8.1	38.07 + 93.9	29.0	65.2
Tocopherols and tocotrienols, mg/kg				
α-tocopherol	3.2	10.8 + 4.5	4.1	19.7
α-tocotrienol	2.4	9.3 + 2.2	5.4	12.8
γ- tocopherol	32.7	69.0 + 8.6	52.7	81.4
γ-tocotrienol	8.6	14.0 + 2.9	7.6	17.5
δ-tocopherol	10.1	18.2 + 3.6	10.0	24.3
Total tocopherols	57.0	121.3 + 16.9	90.8	141.2
Xanthophylls, μg/kg				
Lutein	385	627 + 218	447	1,343
Zeaxanthin	63	95 + 50	ND	243
Total xanthophylls	448	697 + 257	447	1,586
Ferulic acid, mg/g				
Free ferulic acid	0.01	0.042 + 0.016	0.018	0.087
Total ferulic acid	2.50	7.455 + 0.675	6.774	9.511

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