CHAPTER 9

Physical and Chemical Characteristics Related to Handling and Storage of DDGS

Introduction

COMPARED TO OTHER FEED INGREDIENTS, DDGS HAS SOME UNIQUE PHYSICAL AND CHEMICAL CHARACTERISTICS that affect storage and handling characteristics. The use of DDGS in livestock, poultry, and aquaculture feeds has created challenges in several stages of the ingredient handling, transport, storage, and manufacturing including difficulty unloading rail cars, containers and bulk vessels; difficulty with moving and storing DDGS using conventional feeder screws and storage bins; pellet quality and production rates (discussed in detail in **Chapters 17, 22** and **25**), and managing nutrient variability to avoid the risk of compound feeds not meeting desired nutrient specifications (discussed in detail in **Chapters 7, 21** and **24**).

Proper feed ingredient storage is essential for preserving nutritional value and preventing spoilage. The original condition of a feed ingredient is the most important factor affecting preservation of quality during storage, and is influenced by moisture content, relative humidity and temperature (Mills, 1989). Moisture within a feed ingredient ultimately reaches equilibrium with the air within and between particles over time, and depending on the conditions, may lead to the growth of molds and other deleterious microorganisms (Mills, 1989). Maximum acceptable moisture concentrations of grains have been established and vary among grain type for different storage periods (Mills, 1989). Furthermore, maximum relative humidity levels have been established to prevent mold growth (less than 70 percent), bacteria growth (less than 90 percent), and storage insects (less than 60 percent; Mills, 1989) of grains. However, it is important to remember moisture and relative humidity interact with temperature in the storage environment. High temperatures of grain and feed ingredients at the time of loading a storage bin can be maintained for many months if the mass is aerated. Temperature and moisture content determine the extent of enzymatic and biological activities of the grain or ingredient, and temperature differences within the stored mass can increase the risk of mold growth through moisture migration (Mills, 1989). Unfortunately, no studies have been conducted to determine optimal storage conditions to maintain DDGS quality and prevent spoilage over extended periods of time or under various climatic conditions. As a result, it is generally assumed drying DDGS to a moisture content less than 12 percent is acceptable under moderate temperatures and humidity during storage.

Storage Bin Space Allocation

When a new feed ingredient is used for the first time in a commercial feed mill, appropriate storage space must be identified or constructed. It is unusual a feed mill would have an open bin or unused storage space to accommodate a new ingredient. While a simple solution is to decide to discontinue using an existing ingredient and designate that storage bin for the new ingredient, it is very difficult to do this without disrupting the feed manufacturing process (Behnke, 2007). If the bin volume, hopper configuration, and feeder screw design are not suitable for the new ingredient, exploring other options are necessary (Behnke, 2007). When deciding feed ingredient allocation to storage bins, one of the most important considerations is determining the expected diet inclusion rates in all feeds manufactured to calculate daily or monthly usage rate and frequency of use (Behnke, 2007). Perhaps the second most important consideration is related to the physical properties such as bulk density and flow characteristics of the ingredient.

Bridging, Caking and Flowability of DDGS

One of the greatest challenges for handling DDGS is its propensity for bridging, caking, and poor flowability when attempting to unload it from rail cars, containers, and bulk vessels. Flowability is defined as "the relative movement of a bulk of particles among neighboring particles or along the container wall surface" (Pelig, 1977). Unfortunately, some DDGS sources have poor flowability and handling characteristics (Bhadra et al., 2008), which has prevented routine use of rail cars for transport, which has led to the development of specially designed unloading equipment for bulk vessels and containers, and has limited its use in livestock and poultry diets because of bridging in bulk storage containers.

Many factors affect the flow of a bulk ingredient (Peleg, 1977) and no single measurement adequately describes flowability (Bhadra et al., 2008). However, while moisture content of DDGS and the relative humidity of the environment are the major contributing factors to bridging, caking and poor flowability, other factors such as particle size, proportion of condensed solubles added to the grains fraction before drying, dryer temperature, moisture content at dryer exit, and others have also been attributed to this problem (Ganesan

et al., 2008a,b,c). Moisture content of DDGS is generally between 10 to 12 percent to avoid spoilage due to mold growth during long-term storage. However, DDGS is also hygroscopic and can gradually increase in moisture content during exposure to humid conditions over a long storage period (Ganesan et al., 2007). The hygroscopic properties of DDGS can lead to bridging, caking and reduced flowability during transport and storage (Rosentrater, 2007).

Because there is limited storage capacity for DDGS at ethanol plants, it is sometimes loaded into transport vessels within a few hours after it exits the dryer before moisture equilibrates. When this occurs, DDGS will harden and become a solid mass in trucks, rail cars and containers, making it very difficult to unload. However, if warm DDGS is allowed to cool so the moisture can equilibrate before loading, flowability is greatly improved. Most ethanol plants today have implemented a minimum 24-hour "curing," or moisture equilibration period before loading to avoid bridging and caking to prevent damage and cost to rail cars during unloading. Ideally, holding DDGS for five to seven days would allow complete moisture equilibration to occur so the liquid bridges formed in the cooled mass can be broken, which will minimize further handling difficulties (Behnke, 2007). Unfortunately, the majority of ethanol plants have only about two to three days of storage capacity during continuous operations, resulting in an inability to provide a five to seven day time period for adequate moisture equilibration.

The equilibrium relationship between moisture content and relative humidity of the surrounding environment for bulk solids is affected by sorption isotherms. A sorption isotherm indicates the corresponding water content at a specific, constant temperature at a specific humidity level. Therefore, as the relative humidity in the storage environment increases, the sorption increases and causes formation of a liquid bridge between particles (Mathlouthi and Roge, 2003). Adsorption (ability to hold water on the outside or inside surface of a material) and desorption (release of water through or from a surface) of moisture under humid conditions is complex and is affected by the carbohydrate, sugar, protein, fiber and mineral concentrations of a feed ingredient (Chen, 2000). Understanding this relationship for DDGS is important in determining critical moisture and relative humidity levels that may cause bridging and caking of DDGS during transport and storage.

Kingsly and Ileleji (2009) showed formation of liquid bridges occurred in DDGS when the relative humidity reached 60 percent. At a relative humidity of 80 percent, DDGS reached maximum moisture saturation, and at 100 percent relative humidity, the liquid bridge formed by adsorption of moisture hardened and led to the formation of a solid bridge as humidity was reduced. These results indicate that increased relative humidity during transport and storage causes irreversible bridging between DDGS particles and leads to particle aggregation (clumping), caking, and reduced flowability.

Pelleting DDGS is another approach a few ethanol plants have attempted to use to improve bulk density and flowability. Researchers at Kansas State University evaluated the use of various conditioning temperatures and pellet die sizes on ease of pelleting, physical properties, and flow characteristics of DDGS, and showed almost any combination of pelleting conditions improved flowability of DDGS (Behnke, 2007). However, this approach has not been implemented in the U.S. ethanol industry for several reasons. First, it would require additional cost for existing ethanol plants because of the need to purchase, install, and operate expensive boilers and pellet mills; would require additional personnel training and labor cost; and would require additional storage space. Furthermore, most DDGS customers are reluctant to purchase pelleted DDGS because they may perceive it as adulterated with other "fillers," may reduce amino acid and nutrient digestibility because of the thermal treatment during the pelleting process and the added cost of re-grinding the pellets before adding it to other ingredients to manufacture complete feeds in commercial feed mills.

Effects of DDGS oil content on flowability

Physical properties of conventional high-oil (Rosentrater, 2006), reduced-oil (Ganesan et al. 2009) and low-oil (Saunders and Rosentrater, 2007) DDGS have been evaluated. Ganesan et al. (2009) showed reduced-oil DDGS may have improved flow properties compared to conventional high-oil DDGS, but both types were classified to have "cohesive" properties, which suggests that regardless of oil content, DDGS is prone to bridging and caking problems during long-term storage. These researchers suggested that chemical composition and particle surface morphology (roughness, size and shape) may have a greater effect of DDGS flowability than oil content.

As previously discussed, extended storage time for more complete moisture equilibration and pelleting DDGS are not currently viable options for preventing handling and flowability challenges, several new unloading equipment designs have been developed and are being used to facilitate unloading of DDGS from rail cars and containers. For example, stationary devices are located above a rail car pit and use a steel spear to break the hardened mass before unloading. Although these methods improve the time of unloading, they also increase labor and equipment cost. Furthermore, many commercial feed mills have chosen to use flat storage rather than bin or silo storage of DDGS to avoid flowability problems with handling DDGS. The main advantage of flat storage is it adequately addresses the flowability problems and requires lower short-

term capital investment compared with constructing silos. However, flat storage is much more labor intensive, requires front-end loading equipment to move the material, increases the risk of contamination with other ingredients within the storage facility and increases "shrink" losses.

Effects of adding flow agents to DDGS

The addition of various flow agents has been another approach attempted to improve flowability of DDGS, but only a few studies have been conducted to evaluate their effectiveness. Ganesan et al. (2008a) evaluated the effects of adding calcium carbonate to DDGS comprised of varying moisture and condensed distillers solubles content in a laboratory setting, and showed no benefits for improving flowability. Johnstonet al. (2009) evaluated flowability after adding dry matterX-7 (2.5 kg/metric ton; Delst, Inc. Temecula, CA), 2 percent calcium carbonate (ILC Resources, Inc., Des Moines, IA), or 1.25 percent clinoptilolite zeolite (St. Cloud Mining Co., Winston, NM) to DDGS containing either 9 percent or 12 percent moisture. After flow agents were added and mixed with DDGS at the ethanol plant, trucks were loaded, traveled 250 km, were parked and motionless for 60 hrs, followed by transporting another 250 km back to the ethanol plant where it was unloaded, and flowability measurements were obtained. Outdoor temperatures on each of the four days (over a two month period) ranged from 12.9 to 27.8°C, and outdoor relative humidity ranged from 34 to 67 percent. Average particle size of the DDGS source used in this experiment ranged from 584 to 668 μm. The flow rate during unloading of each truckload of DDGS was improved by adding zeolite (558 kg/min) compared with dry matterX-7 (441 kg/min), but these treatments were not different from the control (no flow agent; 509 kg/min) and the calcium carbonate (512 kg/min) treated DDGS loads. Furthermore, flowability score (1 = free flowing, 10 = badly bridged) was improved when zeolite was added to DDGS (4.0) compared with the control (6.0), dry matterX-7 (6.5) and calcium carbonate (5.5). Moisture content at the time of loading was the most important predictor (explained 70 percent of the variation) of flow rate of DDGS, where each 1 percent increase in moisture content from 9 percent, decreased unloading rate by 100 kg/min. Similar results were reported by Ganesan et al. (2008b) where increasing moisture content of DDGS reduced flowability. Ganesan et al. (2008b) also reported that as the Hunter b* score (yellowness of color) increased in DDGS, flow rate also increased, but this only accounted for 4 percent of the variation in flow rate. These results indicate that the most effective criteria from improving flow rate in DDGS is to dry it to lower (9 percent) moisture content, and the addition of dry matter X-7, calcium carbonate and zeolite had no significant benefits for improving flow of DDGS during unloading from trucks.

Effects of Bulk Density on Freight Weight and Particle Segregation of DDGS

Maintaining consistent bulk density of DDGS when loading rail cars and containers has been a challenge for both marketers and buyers because of the desire to achieve consistent freight weights in sequentially loaded rail cars and containers to minimize shipping costs (Ileleji and Rosentrater, 2008). Bulk density varies among DDGS sources, has been reported to range from 391 to 496 kg/m^3 (Rosentrater, 2006) and 490 to 590 kg/m^3 (Bhadra et al., 2009). Clementson and Ilelejie (2010) suggested differences in bulk density observed during loading of rail cars may be due to particle segregation. This is likely to occur because DDGS is a granular bulk solid with particles of various sizes, densities and morphological characteristics found in the structural components of corn grain (Ileleji et al., 2007). Particle segregation was shown to occur during handling and gravity discharge of DDGS (Ileleji et al., 2007; Clementson et al., 2009). Clementson and Ilelejie (2010) conducted a study to evaluate bulk density variation of DDGS when filling and emptying hoppers to simulate loading of rail cars at an ethanol plant, and showed that variation in bulk density occurred as DDGS is loaded and emptied, and was mainly attributed to particle segregation. These researchers showed that after filling, the finer, smaller and denser particles were concentrated in the center of the hopper, while the larger, coarser and less dense particles were concentrated on the sides of the hopper. This phenomenon not only causes variation in bulk density during transloading of DDGS, but it should also be considered when sampling DDGS for nutrient analysis because the location of sampling can influence the mixture of segregated particles and ultimately affect the analytical results (Clementson et al., 2009).

Effect of Storage Bin Design and Particle Size on Flowability of DDGS Diets

Effects of feed storage bin design

Flowability of DDGS is not only a challenge during loading, transport, storage and feed manufacturing, but it can also create challenges on swine farms when DDGS diets are fed in meal form. Suboptimal feed flow can reduce the rate of feed delivery to feeders and bridge in feeders which can lead to out-of-feed events, which can increase stress and the likelihood of gut health problems and reduced growth performance in pigs (Hilbrands et al., 2016). This problem is a greater concern when there is an economic incentive to increase diet inclusion rates of DDGS to 30 percent or more in swine diets, especially when meal diets with small particle size are fed to improve feed conversion of pigs, which is commonly done in the U.S. Storage bin design can be a significant cause or a potential solution to the

flowability problems with feed containing DDGS. Hilbrands et al. (2016) conducted a study to evaluate feed flow from three commercially available feed storage bins. The three bin designs consisted of: 1) a galvanized steel, smooth-sided, seamless bin with a 60 degree round discharge cone (Steel60), 2) a galvanized, corrugated steel bin with a 67 degree round discharge cone (Steel67), and 3) a white, polyethylene bin with a 60 degree round discharge cone (Poly60). The bin styles were chosen to represent differences in slopes of the sides of discharge cones, as well as different construction materials in the bin walls. Diets used in this study contained 55 percent corn, 35 percent soybean meal, 40 percent DDGS, and 2 percent minerals and vitamins, and were ground to an average particle size ranging from 736 to 1,015 microns. The study was conducted in two experiments during the summer and fall seasons. During the summer season, daily high and low temperatures ranged from 30.9°C to 16.6°C, and daily relative humidity ranged from 39.4 to 100 percent. During the fall season, daily high and low temperatures ranged from 2.9°C to 23.7°C, and daily relative humidity ranged from 23.3 to 92.7 percent.

Feed flow rate out of bins was faster from Poly60 bins compared with Steel60 bins, with feed flow rate from Steel67 bins being intermediate (**Table 1**). However, it was interesting the Steel60 bins with the slowest flow rate required the fewest number of taps to keep feed flowing during discharge. As shown in **Table 2**, the presence of a passive agitator increased feed flow rate among all bin designs compared with bins without agitators, but the presence of agitators in Poly60 bins resulted in greater feed flow rate than the presence of agitators in steel bins. However, unlike results in the first experiment, there was no difference in the number of taps required to establish feed flow among the six bin design combinations.

These results indicate that feed bin design affects the flow rate during discharge of meal diets containing 40 percent DDGS. The Poly60 bin provided the best feed flow and highest discharge rates compared with the steel bin designs evaluated, and installing passive agitators increase feed flow in all bin designs.

Table 1. Effect of bin design and temperature and humidity conditions in the headspace on feed flowability (adapted from Hilbrands et al., 2016)[1]

Experiment 1

Measurement	Steel60	Poly60	Steel67
Average temperature, °C	23.6	22.9	22.6
Average humidity %	55.3	54.7	53.9
Feed flow, kg/min	603[a]	737[b]	663[ab]
Taps required[2]	3.8[a]	7.5[b]	6.0[b]
Flowability score[3]	3.7[a]	4.9[b]	4.2[ab]

[1]Means with different superscript letters are different (P less than 0.05).

[2]Number of taps on the side of the bin required during discharge.

[3]Subjective score assigned to flowability (1 = free flowing, 10 = completely bridged)

Table 2. Effect of bin design, passive flow assist agitators, and temperature and humidity conditions in the headspace on feed flowability (adapted from Hilbrands et al., 2016)[1]

Experiment 2

Measurement	Steel60		Poly60		Steel67	
	No agitator	Agitator	No agitator	Agitator	No agitator	Agitator
Avg. temperature, °C	20.1	20.4	19.6	19.5	19.0	18.8
Avg. humidity %	58.3	65.0	65.0	61.3	61.1	63.8
Feed flow, kg/min	827a	827a	831a	970b	807a	880a
Taps required[2]	2.1	2.0	5.2	2.5	3.2	2.0
Flowability score[3]	2.3	2.6	4.2	2.9	3.7	2.3

[1]Means with different superscript letters are different (P less than 0.05).

[2]Number of taps on the side of the bin required during discharge.

[3]Subjective score assigned to flowability (1 = free flowing, 10 = completely bridged)

Effects of particle size

Particle size among DDGS sources is highly variable, with an average of 660 μm and a standard deviation of 440 μm (Liu, 2008). Particle size of DDGS not only contributes to its flow properties (Ganesan et al., 2008a,b,c), but also affects metabolizable energy (ME) content and nutrient digestibility (Mendoza et al., 2010). To further evaluate the effects of DDGS particle size on ME content and nutrient digestibility for growing pigs, Liu et al. (2012) determined the ME content and nutrient digestibility of the same source of DDGS ground to three particle sizes (818 μm = coarse, 594 μm = medium, and 308 μm = fine). These researchers also evaluated flowability of diets containing 30 percent DDGS. As expected, ME content of DDGS improved as the particle size was reduced, where each 25 μm reduction in average particle size (between 818 and 308 μm) increased the ME content of the diet by 13.5 kcal/kg of dry matter. However, there were no effects of DDGS particle size on nitrogen and phosphorus digestibility. Diet flowability was reduced in the 30 percent DDGS diets compared with the control corn-soybean meal diet, and was lowest in the diet containing finely ground DDGS (determined by measuring the drained angle of repose). When flowability of these diets was determined using poured angle of repose as the measurement criteria, there were no differences in flowability between the control and 30 percent DDGS diets, nor were there differences among diets containing different particles sizes of DDGS.

Risk of Mold Growth and Mycotoxin Production During Storage of DDGS

Toxigenic fungal species of molds can develop on grains while growing in fields before harvest, as well as after harvest during storage (Suleiman et al., 2013). Consequently, fungal species are often classified as field fungi or storage fungi (Barney et al., 1995). Field fungi can infect corn grains and produce mycotoxins before harvest

at moisture content between 22 to 33 percent, relative humidity greater than 80 percent, and over a wide range of temperatures (10 to 35°C; Williams and MacDonald, 1983; Montross et al., 1999). Most field fungi do not survive during storage, but some species can continue to grow under appropriate storage conditions (Sanchis et al., 1982). Storage fungi also originate from the field and can replace field molds that infected corn grain prior to harvest (Reed et al., 2007). As shown in **Table 3**, storage fungi require a relative humidity greater than 70 percent, and moisture content greater than 12 percent for corn grain (Montross et al., 1999). Additional fungal species may also be introduced after harvest and include Fusarium spp., Rhizopus spp., and Tilletia spp. (Williams and MacDonald, 1983; Barney et al., 1995). Because DDGS is produced from corn grain, it is reasonable to assume these same molds may be present in DDGS. However, due to the unique physical and chemical properties of DDGS, it is unknown if these relative humidity and moisture conditions apply as they do for corn grain. In fact, DDGS may be more susceptible to mold growth than corn grain because mechanical damage of corn grain during and after harvest can provide entry for fungal spores (Dharmaputra et al., 1994), and broken corn kernels and foreign material promote growth of storage molds (Sone, 2001). For more information on recommended analytical methods to determine mycotoxins in DDGS, see **Chapter 7**.

Lipid Peroxidation of DDGS Sources

Effects of feeding peroxidized lipids to pigs and broilers

Corn DDGS contains the highest lipid concentrations of most common feed ingredients used in animal feeds around the world. Lipid peroxidation is a complex chemical chain reaction induced by heat, oxygen, moisture and transition metals (e.g. Cu and Fe), where free-radicals are converted to toxic aldehydes and other compounds (Shurson et

Table 3. Relative humidity and moisture content that support growth of common storage molds in cereal grains at 25°C to 27°C (adapted from Montross et al., 1999)		
Fungal species	**Relative humidity %**	**Moisture content %**
Aspergillus halophilieus	68	12 – 14
Aspergillus restrictus	70	13 – 15
Aspergillus glaucus	73	13 – 15
Aspergillus candidus	80	14 – 16
Aspergillus ochraeus	80	14 – 16
Aspergillus flavus	82	15 – 18
Aspergillus parssiticus	82	15 – 18
Penicillium spp	80 – 90	15 – 18

al., 2015). Corn oil present in DDGS consists primarily of polyunsaturated fatty acids, particularly linoleic acid (C18:2, 58 percent), which is highly susceptible to peroxidation (Frankel et al., 1984). When lipids are heated at relatively high temperatures, large quantities of secondary lipid peroxidation products are produced including aldehydes, carbonyls and ketones (Esterbauer et al., 1991). Drying temperatures used to produce DDGS can be as high as 500°C, which makes it susceptible to lipid peroxidation. All of the pro-oxidation conditions (heat, oxygen, moisture, and transition minerals) are present in ethanol plants that produce DDGS, and DDGS may be further exposed to these factors during transport, storage, and manufacturing complete feeds in commercial feed mills. Therefore, there is some concern about the extent of peroxidation in DDGS after production, and during transport and long-term storage.

Feeding peroxidized lipids to pigs and broilers has been shown to reduce growth performance and increase oxidative stress. Hung et al. (2017) conducted a meta-analysis using swine and poultry data from 29 publications that showed an average reduction in ADG (5 percent), ADFI (3 percent), gain:feed (2 percent) and serum of plasma vitamin E (52 percent), while increasing serum TBARS (thiobarbituric acid reactive substances; 120 percent) across all studies. Recent reviews by Kerr et al. (2015) and Shurson et al. (2015) provide a comprehensive summary of biological effects of feeding peroxidized lipids to swine and poultry and the challenges of measuring peroxidized lipids and interpreting the results. The lipid peroxidation section in **Chapter 24** of this handbook describes the results from some recent swine feeding trials (Song et al., 2013; Song et al., 2014; Hanson et al., 2015a) which showed inconsistent growth performance responses from feeding a highly peroxidized DDGS diet to pigs.

Survey of lipid peroxidation indicators among DDGS sources

Song and Shurson (2013) evaluated measures of lipid peroxidation and color of 31 corn DDGS sources obtained from ethanol plants in nine states in the U.S., and compared these values with a sample of corn as a reference (**Table 4**). Peroxide value and TBARS (thiobarbituric acid reactive substances) are two common measures of lipid peroxidation used in the feed industry for many years. However, these peroxidation indicators have several limitations like all other measures of peroxidation and therefore, are not always reflective of the true extent of peroxidation of lipids (Hung et al., 2017; Shurson et al., 2015). Currently, there are no standards or guidelines for measuring lipid peroxidation in feed ingredients. However, Wang et al. (2016) suggested that 4-hydroxynonenal and a ratio of select aldehydes provide better estimates of the actual extent of peroxidation in vegetable oils. Unfortunately, these analytical procedures are not commonly used in commercial laboratories.

Peroxide value (PV) has been used to estimate the extent of peroxidation during the initiation phase of the peroxidation process. The PV of the DDGS samples was highly variable (CV = 97.5 percent), with a minimum value of 4.2 and maximum value of 84.1 meq/kg oil. The TBARS value has been used as an estimate of the extent of lipid peroxidation during the propagation phase of peroxidation, which is when the majority of aldehydes are produced. There was less variability (CV = 43.6 percent) in TBARS values among DDGS sources compared with PV values, and ranged from 1.0 to 5.2 ng MDA equiv./mg oil. Both PV and TBARS were greater in DDGS samples compared with the corn reference values, expected because of the thermal processing involved in producing DDGS. Moderate negative correlations were observed for

Table 4. Summary of lipid peroxidation indicators of oil extracted from 31 corn DDGS samples and DDGS color (adapted from Song and Shurson, 2013)

DDGS

Measure	Corn	Average	Median	Minimum	Maximum	CV %
Peroxide value, meq/kg oil	3.1	13.9	11.7	4.2	84.1	97.5
TBARS[1], ng MDA equiv./mg oil	0.2	1.9	1.7	1.0	5.2	43.6
Color						
L*[2]	83.9	54.1	54.9	45.2	58.1	4.6
a*[3]	2.6	10.9	10.8	9.3	12.4	7.2
b*[4]	20.0	37.3	37.5	26.6	42.7	8.8

1TBARS = thiobarbituric acid reactive substances

2L* = a greater value indicates a lighter color.

3a* = a greater positive value indicates a more reddish color.

4b* = a greater positive value indicates a more yellowish color.

colorometric measures between L* and PV (r = -0.63) and b* and PV (r = - 0.57), with slightly greater negative correlations between L* and TBARS (r - -0.73) and b* and TBARS (r = -0.67). These results suggest darker colored and less yellow colored DDGS samples may be more peroxidized.

However, subsequent studies involving the most peroxidzed DDGS source to wean-finish pigs (Song et al., 2014), and sows and their offspring through the nursery phase (Hanson et al., 2016) had no detrimental effects on growth performance. The lack of growth performance responses in these studies may have been a result of the naturally high antioxidant compounds (tocopherols, ferulic acid, lutein, zeaxanthin; Shurson, 2017) present in DDGS, and conversion of sulfur compounds into endogenous antioxidants.

Effects of commercial antioxidants in preventing lipid peroxidation in DDGS

Synthetic antioxidants are commercially available and used to minimize peroxidation in feed fats and oils (Valenzuela et al., 2002; Chen et al., 2014). The most commonly used synthetic antioxidants include t-butyl-4-hydroxyanisole (BHA), 2,6-di-t-butylhydroxytoluene (BHT), t-butylhydroquinone (TBHQ), ethoxyquin, and 2,6-di-ter-butyl-4-hydroxymethyl-phenol (Guo, et al., 2006).

Only one study has been published to evaluate the effectiveness of adding synthetic antioxidants to high- (13 percent crude fat) and low- (5 percent crude fat) oil DDGS (Hanson et al., 2015b). Samples of these two DDGS sources contained either no added synthetic antioxidants (control), or 1,000 mg/kg TBHQ (Rendox; Kemin Industries, Des Moines, IA), or 1,500 mg/kg of ethoxyquin and TBHQ (Santoquin; Novus International, St. Louis, MO). Samples were stored in a temperature (38°C) and relative humidity (90 percent) controlled environmental chamber for 28 days, and subsamples were collected on day 0, 14 and 28 to determine the extent of lipid peroxidation. Results of this study showed significant lipid peroxidation occurred and increased during the 28-day storage period, and the extent of peroxidation was greatest in the high-oil DDGS source compared with the low-oil DDGS source (**Table 5**). However, the addition of either Rendox or Santoquin to either the high- or low-oil DDGS sources reduced peroxidation by about 50 percent. Therefore, these results show that the addition of either Rendox or Santoquin is effective in reducing lipid peroxidation in DDGS when stored up to 29 days in hot, humid conditions. In addition, moisture content of DDGS sources increased from 10.2 percent to 21.4 percent during the 28-day storage period, which led to significant mold growth in all samples.

Table 5. Interactive effects of oil content of DDGS, antioxidant, and sampling day on lipid peroxidation of DDGS source stored at 38°C and 90 percent relative humidity (adapted from Hanson et al., 2015)						
	High Oil DDGS			**Low Oil DDGS**		
Item	**Control**	**Rendox**	**Santoquin**	**Control**	**Rendox**	**Santoquin**
Peroxide value, mEq/kg oil						
Day 14	7.1[a]	3.1[bc]	3.6[b]	4.5[d]	2.7[c]	2.8[c]
Day 28	31.4[a]	13.9[bc]	15.4[b]	20.5[d]	11.7[bc]	13.6[bc]
TBARS[1], mg MDA[2] Eq/kg oil						
Day 14	5.1[a]	2.9[cd]	2.4[d]	3.8[bc]	2.4[d]	2.3[d]
Day 28	21.1[a]	9.5[b]	9.0[b]	14.3[d]	11.0[bc]	10.1[bc]
p-Anisidine value[3]						
Day 14	3.9[a]	1.0[b]	1.0[b]	3.8[a]	0.7[b]	1.0[b]
Day 28	9.1[a]	3.4[bc]	2.9[bc]	9.5[a]	5.0[b]	4.3[b]

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

[1]TBARS = thiobarbituric acid reactive substance

[2]MDA = malondialdehyde

[3]p-anisidine value has no units

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