Chapter 7

Physical and Chemical Characteristics Related to Handling and Storage of DDGS

Introduction

Physical and chemical properties of DDGS vary among sources and can influence its feeding value, handling, and storage characteristics. These include color, smell, particle size, bulk density, pH, color, thermal properties, flowability, shelf life stability, and hygroscopicity. Distiller's dried grains with solubles is characterized as a heterogeneous granular material consisting of a range of particle types, sizes and shapes. Particles included corn fragments (i.e. tip cap, and pericarp tissues), non-uniformly crystallized soluble protein and lipid coatings on the surface of these fragments, and agglomerates (i.e. "syrup balls") that are formed during the drying process (Rosentrater, 2012). These characteristics affect handling, flowability, and storage behavior of DDGS.

Physical properties of DDGS vary among and within ethanol plants, and much of this variation is caused by several factors (Rosentrater, 2012) including:

- Raw material (corn) characteristics
- Hammermill settings
- Conditions, additives, and chemicals used during processing
- Proportion of condensed distillers soluble added to wet distillers grains before drying
- Type of dryer used
- Drying time and temperature
- Cooling and conditioning of DDGS after drying
    - Flat storage vs. vertical silo
    - Final moisture content
    - Cooling time prior to shipping
    - Loading into transport vehicles and containers when hot
    - Ambient temperature and humidity

Considerable research has been conducted during the past few years to measure various physical properties, particularly focused on flowability of DDGS (Rosentrater, 2006a; Ganesan et al., 2008a,b). Rosentrater (2006a) collected DDGS samples from 6 dry grind ethanol plants in eastern South Dakota in 2004 to determine moisture, water activity, thermal conductivity, thermal resitivity, thermal diffusivity, bulk density, angle of repose, and color measures by Hunter L*, a*, and b*, and the results are shown in **Table 1**.

Table 1. Average and range of physical properties of 144 samples of DDGS from 6 dry grind ethanol plants [1]

Physical Property	Minimum	Maximum	Mean
Moisture content, %	13.4	21.2	14.7
Water activity, -	0.53	0.63	0.55
Thermal conductivity, W/m°C	0.06	0.08	0.07
Thermal resistivity, m°C/W	13.1	15.6	14.0
Thermal diffusivity, mm^2/s	0.13	0.15	0.13
Bulk density, kg/m^3	389.3	501.5	483.3
Angle of repose, °	26.5	34.2	31.5
Color, Hunter L*	40.0	49.8	43.1
Color, Hunter a*	8.0	9.8	8.7
Color, Hunter b*	18.2	23.5	19.4

[1] Rosentrater, 2006.

In general, the variability (standard deviations) among samples within measurement was low except for bulk density. The moisture content averaged 14.7% in these samples which is above the 12% recommended maximum moisture content for feed ingredients to minimize transportation costs and microbiological spoilage (Rosentrater, 2006a). Water activity is a measure of the amount of “free” water available and the susceptibility of the samples for spoilage and deterioration by microorganisms and chemical agents. Thermal conductivity, resistivity, and diffusivity describe the ability of a material to conduct heat, resist heat, or diffuse heat, respectively. Sources of DDGS have thermal conductivity values ranging from 0.06 to 0.08 W/(m°C) and thermal diffusivity values ranging from 0.13 to 0.15 mm^2/s (Rosentrater, 2012). Bulk density is an important factor in determining the storage volume of transport vehicles, vessels, containers, totes, and bags. Bulk density affects transport and storage costs. Low bulk density ingredients have higher cost per unit of weight. It also affects the amount of ingredient segregation that may occur during handling of complete feeds. High bulk density particles settle to the bottom of a load during transport, whereas low bulk density particles rise to the top of a load. Angle of repose is a measure of flowability of a substance and color l* is the lightness or darkness of color, a* is the redness or greenness of color, and b* is the yellowness or blueness of color.

Color

Color of corn DDGS can vary from very light, golden yellow in color to very dark brown in color. A detailed summary of the relationship of DDGS color to quality and nutritional value is found in **Chapter 8**. Color is measured in the laboratory using either Hunter Lab or Minolta colorimeters which are used extensively in the human food and animal feed industries to measure the extent of heat damage (browning) in heat processed foods (Ferrer et al., 2005) and feed ingredients (Cromwell et al., 1993). These colorimeters are now commonly used to measure color characteristics of DDGS sources in the U.S. ethanol industry. Lightness or darkness of color is determined by the L* reading (0 = dark, 100 = light), the a* reading measures the redness of color and the b* reading measures the yellowness of DDGS color. Bhadra et al. (2007) reported that L* ranged from 36.6 to 50.2, a* ranged from 5.2 to 10.8, and b* ranged from 12.5 to 23.4 among DDGS sources.

Several factors affect DDGS color including the amount of solubles added to grains before drying, type of dryer and drying temperature used, and the natural color of the feedstock grain being used. The color of corn kernels can vary among varieties and has some influence on final DDGS color. Corn-sorghum blends of DDGS are also somewhat darker in color than corn DDGS because of the bronze color of many sorghum varieties.

When a relatively high proportion of solubles are added to the mash (grains fraction) to make DDGS, the color becomes darker. Noll et al. (2006) conducted a study where they evaluated color in batches of DDGS where approximately 0, 30, 60, and 100% of the maximum possible of syrup was added to the mash before drying. Actual rates of solubles addition to the mash were 0, 12, 25, and 42 gallons/minute. As shown in **Table 2**, increasing solubles addition rate to the mash resulted in a decrease in L* (lightness of color) and b* (yellowness of color), with an increase in a* (redness of color). Similar results were also reported by Ganesan et al. (2005).

Table 2. The Effect of the Rate of Solubles Addition to Mash on Color Characteristics of DDGS.

Color (CIE Scale)	0 gal/min	12 gal/min	25 gal/min	42 gal/min	Pearson Correlation	P Value
L*	59.4	56.8	52.5	46.1	- 0.98	0.0001
a*	8.0	8.4	9.3	8.8	0.62	0.03
b*	43.3	42.1	40.4	35.6	- 0.92	0.0001

Adapted from Noll et al. (2006).

Dryer temperatures in dry-grind ethanol plants can range from 127 to 621ºC. The amount of time DDGS spends in the dryer also influences the color. In general, the higher the dryer temperature and the longer DDGS remains in the dryer, the darker the resulting DDGS will be. The amount and length of heating is highly correlated to color and lysine digestibility and due to the wide range in dryer temperatures, there is a wide range in lysine digestibility that exists among DDGS sources.

When heat is applied to feed ingredients, a browning or Maillard reaction occurs resulting in the formation of high molecular weight polymeric compounds known as melanoidins. The degree of browning (measured via absorbance at 420 nm) is used to assess the extent the Maillard reaction has taken place in foods. Digestibility of lysine is affected by the extent of the Maillard reaction. Lightness and yellowness of DDGS color have been shown to be reasonable general predictors of digestible lysine content among corn DDGS sources for poultry (**Figure 1**; Ergul et al., 2003) and swine (Cromwell et al., 1993; Pederson et al., 2005). However, among sources of corn DDGS, Ergul et al., (2003) showed that true lysine digestibility coefficients ranged from 59 to 83% for poultry, and Stein et al. (2005) showed a similar range in true lysine digestibility coefficients for swine (44 to 63%). In a more robust study, Urriola (2007) evaluated the relationship between L* of DDGS sources and digestible lysine content for swine and found that this relationship was poor for samples with L* greater than 50, and an improved, but still poor relationship for DDGS samples with L* less than 50. Cromwell et al. (1993) evaluated the relationship between Hunter Lab color scores of various sources of DDGS and acid detergent insoluble nitrogen on growth performance of pigs (**Table 3**).

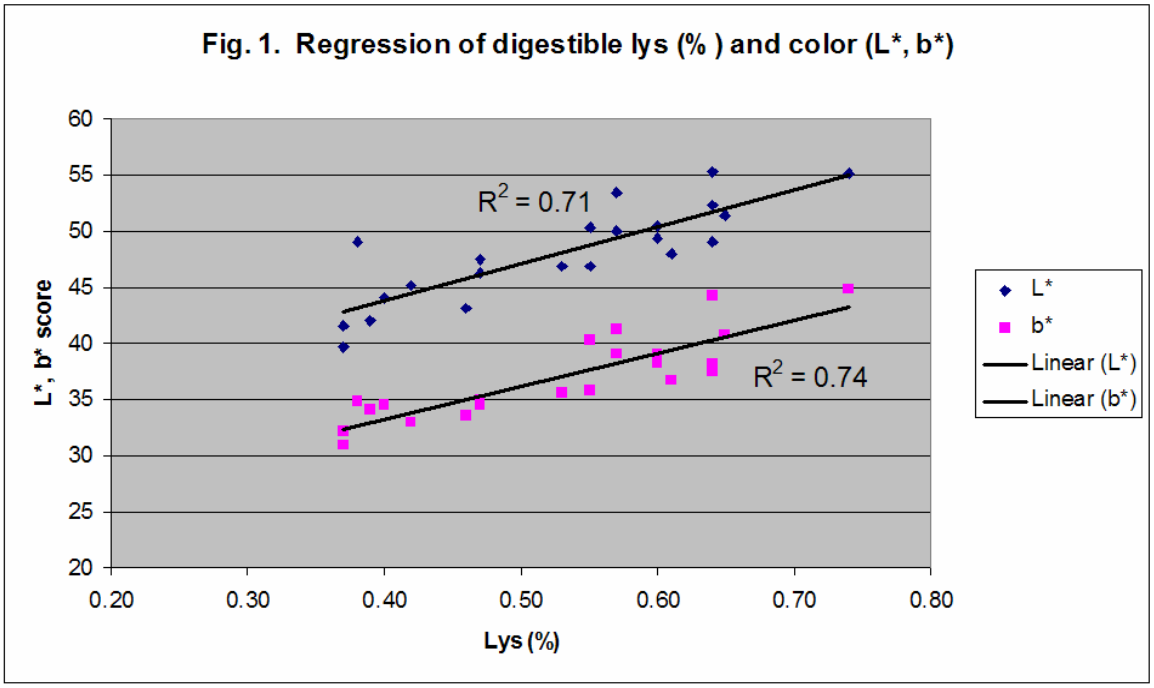

Table 3. Effect of Acid Detergent Insoluble Nitrogen (ADIN) and Color Score on Growth Performance of Pigs Fed Three Blended Sources of DDGS [1]

DDGS Source	L*[b]	a*[b]	b*[b]	ADIN, %	ADG, g[a]	ADFI, g[a]	F/G[a]
A	29.0	6.5	12.7	27.1	218	1,103	5.05
E	31.1	6.1	13.1	36.9			
G	38.8	6.8	16.5	16.0	291	1,312	4.52
I	41.8	6.5	18.8	26.4			
B	53.2	4.7	21.8	8.8	390	1,416	3.61
D	51.7	7.1	24.1	12.0			

[1]Cromwell et al., 1993.
[a] Significant differences among diets (P < .01).
[b] L* = lightness of color (0 = black, 100 = white). The higher the a* and b* values, the higher amount of redness and yellowness, respectively.

Some dry-grind ethanol plants use process modifications to produce ethanol and DDGS. For example, some plants use cookers to add heat for fermentation and as a result, use less enzymes, while other plants will use more enzymes and do not rely on the use of cookers to facilitate fermentation. Theoretically, use of less heat could improve amino acid digestibility of DDGS, but no studies have been conducted to determine how these processes impact final nutrient composition and digestibility.

Smell

High quality, golden DDGS has a sweet, fermented smell. Dark colored DDGS sources that have been overheated have a burned or smoky smell.

Particle Size and pH

Particle size and particle size uniformity of feed ingredients are important considerations for livestock and poultry nutritionists when selecting sources and determining the need for further processing when manufacturing complete feeds or feed supplements. Particle size affects nutrient digestibility, mixing efficiency, amount of ingredient segregation during transport and handling, pellet quality, bulk density, palatability, sorting of meal or mash diets, and the incidence of gastric ulcers in swine.

Bulk density is an important factor to consider when determining the storage volume of transport vehicles, vessels, containers, totes, and bags. Bulk density affects transport and storage costs. Low bulk density ingredients have higher cost per unit of weight. It also affects the amount of ingredient segregation that may occur during handling of complete feeds. High bulk density particles settle to the bottom of a load during transport, whereas low bulk density particles rise to the top of a load.

Several unpublished studies conducted at the University of Minnesota have shown that particle size among DDGS sources is highly variable. In a 2001 study, the average particle size among 16 ethanol plants was 1282 microns (SD = 305, CV= 24%), and ranged from 612 microns to 2125 microns. Two additional DDGS nutrient analysis and physical characteristics surveys were conducted by researchers at the University of Minnesota in 2004 (34 samples from ethanol plants in 11 different states) and 2005 (35 samples). As shown in **Tables 4 and 5**, average particle size ranges between 665 to 737 μm, but the range in particle size is extremely large 73 to 1217 μm. The pH of DDGS sources averages 4.1 but can range from 3.6 to 5.0.

Table 4. Particle Size, Bulk Density, and pH of 34 DDGS Sources Analyzed in 2004.

	Average	**Range**	**SD**	**CV, %**
Particle size, μm	665	256 - 1087	257.48	38.7
Bulk density, lbs/ft^3	31.2	24.9 – 35.0	2.43	7.78
pH	4.14	3.7 – 4.6	0.28	6.81

Table 5. Particle Size, Bulk Density, and pH of 35 DDGS Sources Analyzed in 2005.

	Average	**Range**	**SD**	**CV, %**
Particle size, μm	737	73 – 1217	283	38.0
Bulk density, lbs/ft^3	25.2	22.8 – 31.5	8.6	34.2
pH	4.13	3.6 – 5.0	0.33	7.91

Recent studies have been conducted to evaluate particle size variation and characteristics in DDGS. Liu (2009) conducted a study to evaluate the effect of particle size distribution of ground corn and its effects on the particle size distribution in DDGS. To do this, he analyzed 6 ground corn samples and their corresponding DDGS for particle size distribution, using a series of 6 US standard sieves: Numbers 8, 12, 18, 35, 60, and 100, and a pan. Individual corn and DDGS samples had variable geometric mean diameter of particles, and the average diameter of DDGS particles was greater than that of corn (0.696 vs. 0.479 mm), indicating that during conversion of corn to DDGS, certain particles become larger. The relationship between diameter and mass frequency of individual particle size categories varied, but the particle size distribution of the whole sample was correlated between them (r = 0.81). When comparing the nutrient composition of corn to DDGS, crude protein, oil, ash, total non-starch carbohydrates were concentrated 3.59, 3.40, 3.32, 2.89 times more than found in corn. Although there were positive correlations between protein and non-starch carbohydrate content L* color values between corn and DDGS, the variation in nutrients and color attributes were greater in DDGS than in corn. The variation was larger in the separated fractions than in the whole fraction for both corn and DDGS. Liu (2009) concluded that the physical and chemical characteristics of the raw material (corn), processing method, and addition of yeasts are among the major factors that cause large variations in particle size among DDGS sources.

Liu (2008) obtained 11 corn DDGS samples from different ethanol plants in the U.S. Midwest, and determined particle size distribution of each sample using a series of six selected US standard sieves: Nos. 8, 12, 18, 35, 50, and 100, and a pan. Particle size among and within DDGS samples was highly variable, averaging 0.660 mm for the geometric mean diameter of particles, and a geometric mean standard deviation average of 0.440 mm of particle diameters by mass. The majority had a unimodal particle size distribution, with a mode in the size class between 0.5 and 1.0 mm. Particle size distribution and color were poorly correlated with nutrient composition of DDGS samples, but the distribution of nutrients and color values were highly correlated with particle size distribution. In various separated fractions of DDGS, the protein content, L* and a* color values were negatively correlated, while oil and total CHO content were positively correlated with particle size. These results suggest that it is possible to fractionate DDGS to concentrate certain nutrients based on particle size, and the particle size distribution can be used as an index for potential of DDGS fractionation.

Clementson et al. (2009) investigated the occurrence of particle segregation within piles of DDGS formed by gravity discharge and its effects on subsequent spatial nutrient variability. Particle segregation tests were conducted using piles of DDGS that were formed in a laboratory using DDGS samples from an "old" and a "new" generation fuel ethanol plant. Tests were also performed in a plant study creating piles of DDGS formed from the same two fuel ethanol plants. In both studies, the DDGS piles were formed by gravity-driven discharge and sampled at various locations from the center of the pile to the periphery. Their results showed that particle segregation does result in significant differences in particle size at the sampled locations of the pile, and that particle size (geometric mean diameter) increased from the core of the pile to the periphery. Crude protein and moisture content were the only nutrients that were correlated with particle size, but the correlation of crude protein with particle size was not consistent, while there was a strong, positive correlation of particle size with moisture. These authors concluded that a standard sampling protocol should be developed to insure accurate nutrient determination in DDGS sources based on variable crude protein and moisture content among different portions of a DDGS pile.

Flowability

Unfortunately, DDGS can have some undesirable handling characteristics related to poor flowability under certain conditions. Reduced flowability, or the potential for reduced flowability in DDGS, has caused rail freight companies to not permit the use of their railcars for transport of DDGS (NCERC, 2005). Therefore, DDGS marketers must use their own rail cars to transport DDGS. Reduced flowability and bridging of DDGS in bulk storage containers and transport vehicles limits the acceptability of some DDGS sources for some customers because feed mills do not want to deal with the inconvenience and expense of handling a feedstuff that does not flow through their feed milling systems.

Flowability is defined as the ability of granular solids and powders to flow during discharge from transportation or storage containments. Flowability is not an inherent natural material property, but rather a consequence of several interacting properties that simultaneously influence material flow (Rosentrater, 2006b). Flowability problems may arise from a number of synergistically interacting factors including product moisture, particle size distribution, storage temperature, relative humidity, time, compaction pressure distribution within the product mass, vibrations during transport, and/or variations in the levels of these factors throughout the storage process (Rosentrater, 2006b). In addition, other factors that may affect flowability include chemical constituents, protein, fat, starch, and carbohydrate levels as well as the addition of flow agents.

Since flow behavior of a feed material is multidimensional, there is no single test that completely measures the ability of a material to flow (Rosentrater, 2006b). Shear testing equipment are the primary equipment used to measure the strength and flow properties of bulk materials. They also measure the amount of compaction as well as the bulk strength of materials (Rosentrater, 2006). Another approach for measuring the flowability of granular materials involves measuring four main physical properties: angle of repose, compressibility, angle of spatula, and coefficient of uniformity (e.g. cohesion) (Rosentrater, 2006b).

Several recent studies have been published regarding the causes of DDGS flowability problems and potential solutions to improve flowability. In a review of research data on the flowability and handling characteristics of bulk solids and powders, Ganesan et al. (2008a), suggested that DDGS flowability may be affected by storage moisture, temperature, relative humidity, particle size, time, or temperature variations, and other factors. Bhadra et al. (2008) evaluated surface characteristics and flowability of DDGS using cross sectional staining of DDGS particles and showed that a higher amount of protein thickness compared to carbohydrate thickness in surface layers from DDGS had lower flow function index, and greater cohesiveness, which indicates possible flow problems. They also observed that higher surface fat occurred in samples with worse flow problems.

Ganesan et al. (2007a) used data obtained from previous work using exploratory data analysis techniques to develop a comprehensive model to predict the flowability of DDGS. A simple and robust model (R^2 = 0.93, SE = 0.12) was developed, but the model was exclusively based on the DDGS from one ethanol plant. Since DDGS flow properties vary among sources, they suggested using this methodology to develop similar models to predict the flowability of DDGS for other plants. In a follow-up study, Bhadra et al. (2009) measured flowability characteristics of DDGS samples from five ethanol plants in the north central region of the U.S. using Carr and Jenike tests, and the resulting data were mathematically compared with a previously developed empirical model. Their assessment of overall flowability suggested that DDGS samples do have the potential for flow problems, although no samples exhibited complete bridging.

Ganesan et al. (2008b) then conducted a study to determine the effect of moisture content and solubles level on the physical, chemical, and flow properties of DDGS. They determined the effect of five moisture levels (10, 15, 20, 25, and 30%) on the resulting physical and chemical properties of DDGS containing 4 levels of solubles (10, 15, 20, and 25%). Results from this study showed that the level of solubles and moisture content had significant effects on physical and flow properties (e.g., aerated bulk density, packed bulk density, and compressibility). The dispersibility, flowability index, and floodability index were used to show that flowability generally declined as moisture moisture content increased for most of the soluble levels evaluated. The color and protein content of the DDGS were also affected as soluble levels increased.

In a subsequent study, Ganesan et al. (2008c) evaluated the flow properties of DDGS with varying soluble and moisture contents using jenike shear testing. Results from this study showed that depending on the solubles level in DDGS, and moisture content above a certain level, that the moisture actually began acting as a lubricant, easing the flow of the DDGS. They also observed that with the addition of higher levels of solubles and moisture, the compressibility of DDGS increased. They concluded that DDGS is a cohesive material, and it is likely to produce cohesive arching problems.

In attempts to improve DDGS flowability, two studies have been conducted to determine the effects of adding selected flow agents to DDGS on flowability (Ganesan et al., 2008d; Johnston et al., 2009). Ganesan et al. (2008) evaluated the effect of 0, 1, and 2% calcium carbonate addition to DDGS with variable moisture content and soluble levels. Flowability of DDGS was reduced when percentage of solubles and moisture content increased. Adding the flow agent ($CaCO_3$) did not improve the flow properties of DDGS, which may have been due to the lack of surface affinity between DDGS and the flow agent particles, or too little inclusion of the flow agent. Similarly, Johnston et al. (2009) conducted a study to evaluate the addition of a moisture migration control agent at 2.5 kg/metric ton (DMX-7), calcium carbonate at 2%, or a clinoptilolite zeolite at 1.25%. The experiment was conducted at a commercial, dry-grind ethanol plant using DDGS at two different moisture levels (9 vs. 12%). Flow rate of DDGS at unloading was higher for the 9% compared with 12% moisture level (620 vs. 390 kg/min). Flow rates of DDGS at unloading were: 509 (Control), 441 (DMX-7), 512 (Calcium carbonate), and 558 (Zeolite) kg/min. None of the ACA created flow rates that differed significantly from Control. These researchers concluded that increasing moisture content from 9% to 11.6% decreased flowability of DDGS and that the flow agents tested in this study, at the selected concentrations, did not improve flowability of DDGS.

Storage Stability

Moisture

Preservatives and mold inhibitors are commonly added to wet distiller's grains (~50% moisture) to prevent spoilage and extend shelf life. However, since the moisture content of DDGS is usually between 10 to 12%, there is minimal risk of spoilage during transit and storage unless water leaks into transit vessels or storage facilities. It is well accepted in the grain handling and feed industry that moisture content of grain and grain by-products should be less than 15% to prevent heating and spoilage (i.e. molds and mycotoxins) during transport and storage. Therefore, unless the moisture content of DDGS exceeds 15%, the shelf life of DDGS appears to be many months. No research studies have been conducted to demonstrate that preservatives and mold inhibitors are necessary to prevent spoilage and extend shelf life of DDGS.

"Clumping" or "caking" can occur as a result of loading DDGS into trucks, rail cars, or containers if it has not been cooled and "cured" properly before loading. This often causes flowability problems and difficulty unloading DDGS. The addition of flow agents did not improve flowability of DDGS but low moisture content (9%) improved flowability compared to DDGS containing 12% moisture (Johnston et al., 2009).

Fat oxidation

In the past, most corn DDGS sources contained 11 to 12% fat (corn oil) on a DM basis, but with the widespread implementation of corn oil extraction technologies, crude fat content can now range from 5 to 12%. Regardless of crude fat content, the fatty acid profile and characteristics of corn oil do not change appreciably and are shown in **Tables 7 and 8**.

Vegetable oils, like corn oil are high in unsaturated fatty acids. As a result, vegetable oils have a higher unsaturated to saturated fatty acid ratio (U:S) compared to animal fats. The U:S ratio affects the melting point and energy value of fat, as well as the fatty acid composition in liver, fat, meat, and milk of pigs and poultry. The iodine value is a method of estimating U:S ratio. Each double bond in a fatty acid has the capability of taking up two atoms of iodine. By reacting fatty acids with iodine, it is possible to determine the degree of unsaturation of a fat or oil. The iodine value is defined as grams of iodine absorbed by 100 grams of fat. Because unsaturated fats have more double bonds, they will have higher iodine values than saturated fats. Iodine value can be used to estimate fatty acid profiles of various fat sources.

Fats are susceptible to breakdown by oxidation to form peroxides, which are unstable compounds, and can become rancid. Peroxide value is sometimes also referred to as initial peroxide value because it is determined on a sample as submitted. A peroxide value of 5.0 mEq of peroxide/kg or lower is an indication of little or no rancidity. High free fatty acid content may indicate oxidation or breakdown of the fat and potential rancidity. Free fatty acids are those that are not linked to glycerol by an ester linkage, but are in free form. Oxidation of fat produces free fatty acids as a by-product. Moisture in fats and high fat ingredients may increase rancidity. However, this is of relatively little concern in DDGS because the moisture content is typically only 10 to 11%.

Table 7. Selected fatty acids (% total fatty acids) in corn oil.[1]

	≤C16:0	C16:0	C16:1	C18.0	C18:1	C18:2	C18:3	≥C:20
Corn oil	0.0	10.9	0.0	1.8	24.2	59.0	0.7	---

[1] Swine NRC, 1998.

Table 8. Chemical characteristics and energy value of corn oil.[1]

	Total Saturated, %	Total Unsaturated, %	U:S Ratio	Iodine Value	Total ∑ N-6	Total ∑ N-3	DE, kcal/kg	ME, kcal/kg
Corn oil	13.3	86.7	6.53	125	58.0	0.7	8755	8405

[1] Swine NRC, 1998.

In a field study conducted by the U.S. Grains Council, fat stability of U.S. DDGS was evaluated in hot, humid sub-tropical on-farm storage conditions in Taiwan. This study was conducted at a commercial dairy farm in central Taiwan. The DDGS was produced by an ethanol plant in South Dakota and exported to Taiwan in a 40 foot container. Upon arrival in Taiwan, DDGS was re-packaged in 50 kg feed bags with a plastic lining. Bags of DDGS were stored in a covered steel pole barn for ten weeks during the course of the trial. The trial was conducted from September to November 2003, under high temperature and humidity conditions. A random sample of DDGS was obtained weekly from storage and stored in a freezer until analysis for peroxide value and free fatty acid analysis. Analytical results are shown in **Table 9**. Initial and week 10 peroxide values for DDGS were not different and were well below the maximum 5.0 mEq peroxide/kg threshold value for rancidity. Although the level of free fatty acids in oil extracted from DDGS increased slightly from week 1 to week 10, there is no evidence that lipid oxidation (rancidity) occurred in DDGS. This indicates that the fat in DDGS is stable for at least a 10 week storage period in hot and humid climates where the average temperature was 25.4°C (range from 17.1°C to 32.4°C) and the average % relative humidity was 79.9% (range from 41.2% to 99.5%).

Table 9. Peroxide value of DDGS and free fatty acid concentration of oil extracted from DDGS at week 1 and week 10 of storage.

Analysis	**Week 1 Sample**	**Week 10 Sample**
Peroxide value, mEq/kg	0.70	0.60
Free fatty acids, % as oleic	11.2	16.2

Another field study was sponsored by the Minnesota Corn Growers Association in 2003 (www.ddgs.umn.edu), to evaluate DDGS samples (obtained weekly) from storage at commercial feed mill in Jalisco, Mexico for moisture (dry matter), mycotoxins (aflatoxin, ochratoxin, T-2 toxin, fumonisin, and zearalenone), and a measure of fat oxidation (rancidity). Average environmental temperature during the 16-week storage period was 17.0°C, and ranged from an average low of 9.3°C to an average high temperature of 24.7°C. There was no detectable change in oxidative rancidity during the 16-week storage period or presence of mycotoxins.

It is presumed that the apparent stability of corn DDGS is due to the presence of high concentrations of natural antioxidants. Corn contains a high concentration of compounds that have natural antioxidant activity. Adom and Liu (2002) found that corn had the highest total antioxidant activity compared to wheat, oats and rice, and had the highest percentage of bound antioxidants. It is possible that the presence of significant amounts of antioxidants naturally found in corn are likely responsible for excellent stability of DDGS for several weeks of storage, even under hot, humid conditions.

Water Adsorption Properties of DDGS

Limited information exists regarding the water adsorption properties (hygroscopicity; ability to attract moisture) of DDGS. However, the U.S. Grains Council sponsored a broiler field trial in Taiwan, where moisture content of DDGS was monitored during storage at a commercial feed mill from March 16 to June 10, 2004. A random sample of DDGS was obtained weekly from storage at the feed mill and analyzed for moisture over a 13-week storage period. Moisture content of DDGS increased from 9.05% at the beginning of the storage period to 12.26% at the end of the 13-week storage period **(Table 6)**. As expected, crude protein concentration did not change in DDGS, and no aflatoxin was present initially or at the end of the storage period. Therefore, it appears that under humid climatic conditions, DDGS will increase in moisture content during long-term storage.

Table 6. Laboratory analysis results for moisture, crude protein, aflatoxin, of DDGS during storage at the commercial feed mill in Taiwan.

Sample Date	Sample Number	Moisture, %	Crude protein, %	Aflatoxin, ppb
16-Mar-04		9.05	27.60	0.00
17-Mar-04		10.17	27.61	0.00
24-Mar-04	1	10.65	27.59	0.00
31-Mar-04	2	10.70	27.63	0.00
7-Apr-04	3	10.71	27.62	0.00
14-Apr-04	4	10.76	27.73	0.00
21-Apr-04	5	10.93	27.71	0.00
28-Apr-04	6	11.02	27.62	0.00
5-May-04	7	11.28	27.54	0.00
12-May-04	8	11.16	27.61	0.00
19-May-04	9	11.70	27.63	0.00
27-May-04	10	11.88	27.61	0.00
3-Jun-04	11	12.13	27.50	0.00
10-Jun-04	12	12.26	27.53	0.00

Moisture appears to be a major factor affecting DDGS flowability during storage and transport, in which storage moisture, temperature, relative humidity, particle size, and time variations may interact to determine flow characteristics. Ganesan et al. (2008e) conducted a study to develop sorption isotherms for DDGS with varying soluble levels, in order to provide facility designers and operators with relevant storage and transport information. They determined equilibrium moisture content of DDGS with four different soluble levels (10, 15, 20, and 25% on a dry basis) using a static gravimetric method at 10°C, 20°C, 30°C, and 40°C over four equilibrium relative humidity levels of 60, 70, 80, and 90%. They observed that the sorption capacity of DDGS increased with increasing temperature and solubles level, and followed a type III isotherm, which is commonly observed in high-sugar foods. The equilibrium moisture content for DDGS containing 10, 15, 20, and 25% solubles (dry basis) ranged from 8.61 to 47.07% (dry basis), 11.58 to 83.49% (dry basis), 13.72 to 90.70% (dry basis), and 15.03 to 132.01% (dry basis), respectively. These researchers applied 9 models to fit the isotherm data, but learned that no common model could accurately predict the sorption isotherms of DDGS with various soluble levels. As a result, they developed a new equilibrium moisture content model (Ganesan-Muthu-Rosentrater model) that included solubles level in DDGS as one of the effects along with temperature and moisture content. This model, along with a new modified exponential 2 model, produced the best fits for DDGS with varying soluble levels, and can be used to predict equilibrium moisture sorption behavior of DDGS under a variety of storage conditions (Ganesan et al., 2007b).

Pelleting

Pelleting DDGS and complete feeds has a number of advantages compared to the granular form including improved flowability, increased bulk density, reduces waste, dust, and particle segregation, as well as potentially improving palatability and energy digestibility when fed to livestock.

Rosentrater (2007) conducted two studies involving laboratory scale and commercial scale to determine the feasibility of pelleting DDGS. The positive results obtained in the laboratory scale study were reproduced in the commercial scale study. In the commercial scale study, he used a single source of DDGS and used two processing lines representing two different equipment manufacturers (Manufacturer A and Manufacturer B). Processing conditions are described in **Table 7**. The major differences between the two pelleting processes were pellet die length, die length/diameter ratio, conditioned mash temperature, pellet mill exit temperature, and moisture content of conditioned mash, pellet mill exit moisture, and cooler exit moisture.

As shown in **Tables 8 and 9**, nutrient and amino acid composition were mostly unchanged before and after pelleting, and heat damage to protein was negligible. Researchers did observe some slight performance differences between the manufacturing processes.

Table 7. Processing conditions used to pellet DDGS [1]

Parameter	Manufacturer A	Manufacturer B
Pellet die diameter, in.	11/64	11/64
Pellet die length, in.	1 3/4	2 5/8
Length/diameter ratio	10.2	15.3
Ambient temperature, °F	49	49
Conditioned mash temperature, °F	175	155
Pellet mill exit temperature, °F	190	160
Cooler exit temperature, °F	56	55
DDGS moisture, %	11.34	11.34
Conditioned mash moisture, %	17.73	16.08
Pellet mill exit moisture, %	17.57	16.62
Cooler exit moisture, %	13.49	12.80

[1] Rosentrater, 2007.

Table 8. Nutrient content (dry matter basis) of DDGS before and after pelleting.[1]

Nutrient	DDGS	Manufacturer A	Manufacturer B
Moisture, %	10.8	12.1	12.1
Dry matter, %	89.3	87.9	88.0
Crude protein, %	28.8	28.1	28.6
Heat damaged protein, %	2.9	2.8	2.8
Available protein, %	26.0	25.3	25.8
ADF, %	14.3	13.0	15.4
NDF, %	31.4	30.3	28.9
Crude fiber, %	7.1	5.9	6.6
Crude fat, %	11.0	11.1	11.5
Ash, %	3.84	3.98	4.00
Total starch, %	11.7	13.9	12.5

[1] Rosentrater, 2007

Table 9. Amino acid content (dry matter basis) of DDGS before and after pelleting.[1]

Amino acid	DDGS	Manufacturer A	Manufacturer B
Alanine, %	2.50	2.15	2.24
Arginine, %	1.08	1.08	1.29
Aspartic acid, %	1.66	1.68	1.71
Cystine, %	0.80	0.83	0.82
Glutamic acid, %	4.61	4.63	4.69

Glycine, %	1.05	1.01	1.01
Histidine, %	0.76	0.74	0.74
Isoleucine, %	1.00	0.83	0.84
Leucine, %	3.18	3.00	3.10
Lysine, %	0.80	0.81	0.81
Methionine, %	0.59	0.58	0.54
Phenylalanine, %	1.34	1.33	1.37
Proline, %	2.12	2.13	2.15
Serine, %	1.24	1.36	1.30
Threonine, %	0.92	1.01	0.99
Tyrosine, %	1.07	1.11	1.07
Tryptophan, %	0.28	0.24	0.28
Valine, %	1.41	1.08	1.18

[1]Rosentrater, 2007

Pelleting DDGS did cause changes in physical properties (**Table 10**). Pelleting DDGS resulted in darker color, regardless of manufacturer equipment used, but bulk density increased (9 to 20%) and angle of repose (a measure of flowability) decreased 18 to 19% indicating substantially improved flowability for pelleted DDGS. Pellet durability was high (89 to 94%) regardless of the manufacturing equipment used. These results suggest that high quality DDGS pellets can be manufactured without the use of pellet binders. However, pelleting conditions may need to be modified (e.g. pellet die length/diameter ratios) depending on the source of DDGS used.

Table 10. Physical properties of DDGS before and after pelleting.[1]

Property	DDGS	Manufacturer A	Manufacturer B
Water activity, -	0.474	0.538	0.534
L* color	40.66	33.26	34.19
a* color	9.48	5.15	6.01
b* color	20.00	13.64	15.17
Particle size-GMD, mm	0.93	-	-
Particle size-GSD, mm	1.61	-	-
Thermal conductivity, W/m°C	0.07	-	-
Thermal diffusivity, mm^2/s	0.15	-	-
Bulk density, kg/m^3	476.14	571.93	519.50
Angle of repose, °	20.06	16.36	16.21
Unit density, kg/m^3	-	1035.25	938.44
Durability, %	-	93.93	88.87
Mechanical strength, MPa	-	0.51	0.30

Modulus elasticity, MPa	-		5.24		2.41	

[1] Rosentrater, 2007

Xu et al. (2008) conducted a study to evaluate pelleting corn DDGS (3.5 cm in length, 1.5 cm in diameter) utilizing a closed-end die under axial stress from a vertical piston applied by an Instron universal testing machine. The pelleting conditions included DDGS moisture content of 25-35%, processing temperature of 100 to 120°C, pressure of 12.5 to 37.5 MPa, and dwell time of 5 to 15 seconds. They measured pellet density, durability, and stability and observed that moisture content, temperature, and pressure significantly affected the properties of DDGS pellets, but the impact of dwell time was negligible. They also observed that increasing temperature initially increased and then decreased unit density, but high moisture and pressure had positive effects on unit density and pellet durability. As pressure and moisture content increased, the density ratio also increased. The results of this study support the conclusions from the Rosentrater (2007) study that suggest that DDGS can be effectively pelleted over the range of variables evaluated. In this study, the optimum pelleting conditions were 34.6% moisture content (much higher than found in DDGS), 107°C press temperature, and 36.8 MPa pressure, which resulted in maximum durability, density, and acceptable dimensional stability.

Conclusions

The physical characteristics of DDGS are similar to other dry, granular feed ingredients such as soybean meal and corn gluten meal, but moisture content, particle size, and stickiness affect thermal properties, bulk density, and flowability. Particle size and temperature and time of heating during the drying process vary among ethanol plants and affect nutrient digestibility of DDGS. Use of conventional pellet dies and processes in commercial feed mills may result in reduced pellet durability and throughput of pellet mills when manufacturing diets containing DDGS. However, modifying the pelleting conditions according to the guidelines summarized in this chapter can result in acceptable pellet quality when DDGS is included in animal feeds.

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