Chapter 10

Quality and New Technologies to Create Corn Co-Products from Ethanol Production

Jerry Shurson and Abdorrahman S. Alghamdi

The objective of this chapter is to describe the quality characteristics of distillers dried grains with solubles (DDGS) and new technologies used to produce new fractionated corn co-products. Quality of a feedstuff can be defined in many ways, but as described in Webster's dictionary, it is the degree of excellence or superiority. Since corn co-products from ethanol production are sources of nutrients, high quality can be described as containing a consistently high level of economically important nutrients (e.g., energy, amino acids, and phosphorus) that are highly digestible for the animal. Another way of describing quality according to Webster's dictionary is the peculiar and essential character of something. Most corn co-products are produced as a result of the fermentation process used to produce ethanol and contain residual yeast and perhaps other compounds, which may provide additional health and nutritional benefits beyond the nutrients they provide to the animal's diet.

Variability in Nutrient Content and Digestibility of Distillers Dried Grains with Solubles

Perhaps the biggest challenge of using DDGS (referring to corn-based throughout unless otherwise noted) in animal feeds is to know the nutrient content and digestibility of the source being used. The nutrient content of DDGS can vary among U.S. DDGS sources (Table 10.1) and has been shown to vary over time within plants (Spiehs, Whitney, and Shurson, 2002).

Nutritionists want consistency and predictability in the feed ingredients they purchase and use. Because of the high crude protein content of

---

Jerry Shurson is a professor and swine nutritionist in the Department of Animal Science at the University of Minnesota, and Abdorrahman Alghamdi is an assistant professor in the Department of Agriculture Science at Truman State University in Kirksville, Missouri.

Table 10.1. Averages and ranges (%) in composition of selected nutrients (100% dry matter basis) among 32 sources of U.S. corn distillers dried grains with solubles

Nutrient	Average (CV[a]	Range
Crude protein	30.9 (4.7)	28.7 - 32.9
Crude fat	10.7 (16.4)	8.8 - 12.4
Crude fiber	7.2 (18.0)	5.4 - 10.4
Ash	6.0 (26.6)	3.0 - 9.8
Lysine	0.90 (11.4)	0.61 - 1.06
Arginine	1.31 (7.4)	1.01 - 1.48
Tryptophan	0.24 (13.7)	0.18 - 0.28
Methionine	0.65 (8.4)	0.54 - 0.76
Phosphorus	0.75 (19.4)	0.42 - 0.99

Source: www.ddgs.umn.edu.

[a]CV = coefficient of variation (standard deviation divided by the mean x 100).

DDGS, this co-product is often compared to soybean meal, but soybean meal is less variable than DDGS in nutrient content among different sources (Table 10.2). Crude fat was the only nutrient that had a higher coefficient of variation in soybean meal compared to DDGS, which was caused by three extreme values (3.27%, 3.55%, and 3.86%) in the samples collected (Urriola et al., 2006), since the fat content in soybean meal averages only about 1.74%. With the growing diversity of corn co-products coming onto the feed ingredient market, those produced by the ethanol industry are becoming less of a commodity compared to soybean meal because of the wide variability in nutrient content. To manage the variation among DDGS from different sources, some commercial feed manufacturers are beginning to require identity preservation of selected DDGS sources by limiting the number of suppliers in the company's preferred list. Olentine (1986) listed a number of variables in the raw materials and processing factors that contribute to variation in nutrient composition of corn co-products (Table 10.3).

Variation in Nutrient Content of Corn Affects the Nutrient Composition of Distillers Dried Grains with Solubles

Much of the variation in nutrient content of DDGS is likely due to the normal variation among corn varieties and geographic location where the corn is grown. Reese and Lewis (1989) showed that corn produced in Nebraska in 1987 ranged from 7.8% to 10.0% crude protein, 0.22% to 0.32% lysine, and 0.24% to 0.34% phosphorus (Table 10.4). When corn is fermented to produce ethanol and DDGS, the nutrients in DDGS become

Table 10.2. Variability (coefficients of variation, %) of selected nutrients among 32 U.S. sources of distillers dried grains with solubles versus 6 sources of U.S. soybean meal

Nutrient	DDGS	Soybean Meal
Crude protein	4.7	2.3
Crude fat	16.4	30.9
Crude fiber	18.0	9.5
Ash	26.6	6.6
Lysine	11.4	3.0
Methionine	8.4	5.3
Threonine	5.8	4.2
Tryptophan	13.7	7.3
Calcium	117.5	25.8
Phosphorus	19.4	9.1

Source: Soybean meal data is from Urriola et al., 2006.

Table 10.3. Factors influencing nutrient composition of corn co-products produced by the ethanol industry

Raw Materials	Processing Factors
Types of grains	Grind Procedure
Grain variety	Fineness
Grain quality	Duration
Soil conditions	Cooking
Fertilizer	Amount of water
Weather	Amount of pre-malt
Production and harvesting methods	Temperature and time
	Continuous or batch fermentation
Grain formula	Cooling time
	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

Table 10.3. Continued

	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

Source: Olentine, 1986.

Table 10.4. Overall average, minimum, and maximum values for nutrients in corn

Nutrient	Average	Minimum	Maximum
Crude protein, %	8.6	7.8	10.0
Lysine, %	0.26	0.22	0.32
Calcium, %	0.01	0.01	0.01
Phosphorus, %	0.28	0.24	0.34
Selenium, ppm	0.12	0.10	0.16
Vitamin E, IU/lb	3.9	1.9	5.8

Source: Reese and Lewis, 1989.
Note: On 88% dry-matter basis.

two to three times more concentrated, which contributes to the increased variability in nutrient content among DDGS sources.

Variation in the Rate of Solubles Added to Grains Affects the Nutrient Composition of Distillers Dried Grains with Solubles

The ratio of blending condensed distillers solubles with the grains fraction to produce DDGS also varies across ethanol plants. The typical nutrient content of each fraction is shown in Table 10.5. Because there are substantial differences in nutrient composition between these two fractions, it is understandable that the proportion of the grains and solubles blended together will have a significant effect on the final nutrient composition of DDGS. The American Association of Feed Control Officials defines DDGS as follows: "Distillers Dried Grains with Solubles

Table 10.5. Nutrient content and variability (%) of corn distillers grains and distillers solubles (100% dry matter basis)

	Average	Minimum	Maximum
Grains fraction			
Dry matter	34.3	33.7	34.9
Crude protein	33.8	31.3	36.0
Crude fat	7.7	2.1	10.1
Crude fiber	9.1	8.2	9.9
Ash	3.0	2.6	3.3
Calcium	0.04	0.03	0.05
Phosphorus	0.56	0.44	0.69
Solubles fraction			
Dry matter	27.7	23.7	30.5
Crude protein	19.5	17.9	20.8
Crude fat	17.4	14.4	20.1
Crude fiber	1.4	1.1	1.8
Ash	8.4	7.8	9.1
Calcium	0.09	0.06	0.12
Phosphorus	1.3	1.2	1.4

Source: Knott, Shurson, and Goihl, 2004.

is the product obtained after the removal of ethyl alcohol by distillation from yeast fermentation of a grain or a grain mixture by condensing and drying at least three-fourths of the solids of the resultant whole stillage by methods employed in the grain distilling industry."

Some ethanol plants add all of the condensed solubles produced to the grains fraction, while others add substantially less solubles before drying. At least one ethanol plant is attempting to burn most, if not all, of the solubles produced as a fuel source for the ethanol plant. This practice substantially changes the nutrient composition of the resulting distillers dried grains (DDG) compared to the nutrient composition of DDGS.

Ganesan, Rosentrater, and Muthukumarappan (2005) evaluated the effects on protein and fat content of adding 10%, 15%, 20%, and 25% condensed distillers solubles (dry basis) to the grains fractions to produce DDGS (Table 10.6). The fat content of DDGS increased from 8.79% to 11.77% for the 10% and 25% solubles addition, respectively. The protein content decreased from 30.54% to 26.02% with the addition of 10% and 25% solubles, respectively. Therefore, the nutrient content of DDGS can be substantially altered based on the amount of solubles added to the grains fraction.

Table 10.6. Average fat and protein content of distillers dried grains with solubles with four different solubles percentages

Nutrient, % db	10% Solubles	15% Solubles	20% Solubles	25% Solubles	SEM
Fat	8.79[b]	7.53[b]	12.68[a]	11.77[a]	1.7
Protein	30.54[a]	30.16[a]	27.23[b]	26.02[c]	0.26

Source: Ganesan, Rosentrater, and Muthukumarappan, 2005.
[a,b,c] Means within same row not sharing a common superscript are different ($P < .05$).

Variation in the Rate of Solubles Addition to Grains Affects Nutrient Digestibility of Distillers Dried Grains with Solubles

Noll, Parsons, and Walters (2006) evaluated the nutrient composition and digestibility of different DDGS batches produced with varying levels of solubles added to the wet grains. The solubles were added at approximately 0%, 30%, 60%, and 100% of the maximum possible addition to the grains, which corresponds to 0, 12, 25, and 42 gallons of syrup added to the grains fraction per minute. Dryer temperatures decreased as the rate of solubles addition to the grains decreased because less moisture was present in the grains and syrup mixture before going into the dryer. Samples of DDGS were analyzed for color, particle size, moisture, crude fat, crude protein, crude fiber, ash, phosphorus, lysine, methionine, cystine, and threonine. Digestible amino acids were determined using cecectomized roosters, and nitrogen-corrected true metabolizable energy (TME_n) was determined using intact young turkeys. As shown in Table 10.7, increasing the amounts of solubles resulted in darker-colored DDGS (reduced L* and b*; lightness and yellowness) and increased crude fat, ash, TME_n (poultry), magnesium, sodium, phosphorus, potassium, chloride, and sulfur but had minimal effects on crude protein and amino acid content and digestibility.

Effects of Color of Distillers Dried Grains with Solubles on Amino Acid Digestibility

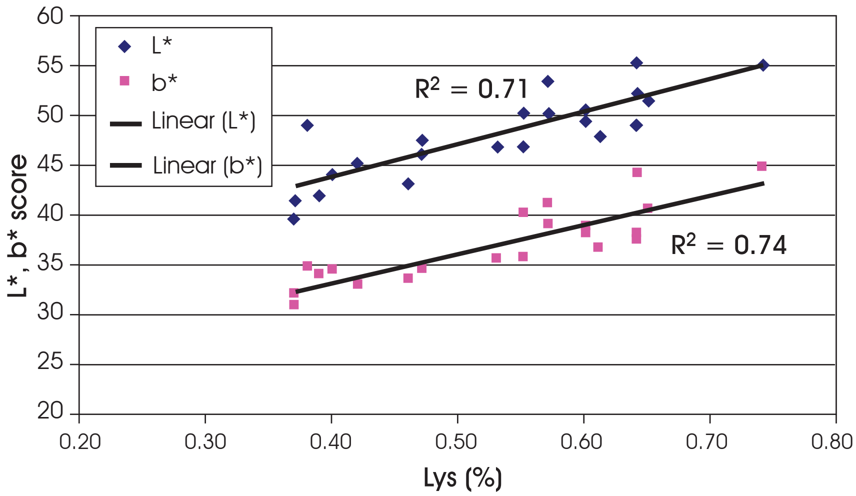
Amino acid digestibility of feed ingredients is very important when evaluating ingredients and formulating diets for swine and poultry. Lightness and yellowness of the color of DDGS appear to be reasonable predictors of digestible lysine content among golden DDGS sources for poultry (Figure 10.1; Ergul et al., 2003) and swine (Pederson, Pahm, and Stein, 2005). True lysine digestibility coefficients ranged from 59% to 83% in poultry (Ergul et al., 2003), and from 44% to 63% in swine (Stein et al., 2006).

Table 10.7. Effects of increasing solubles addition to the grains fraction during production of distillers dried grains with solubles on color, nutrient content, TME_n (poultry), and amino acid digestibility (100% dry matter basis)

Measurement	0 gal/min	12 gal/min	25 gal/min	42 gal/min	Pearson Correlation Coefficient	P Value
Color L*[a]	59.4	56.8	52.5	46.1	- 0.98	0.0001
Color a*[a]	8.0	8.4	9.3	8.8	0.62	0.03
Color b*[a]	43.3	42.1	40.4	35.6	- 0.92	0.0001
Moisture, %	9.52	9.75	10.74	13.83	0.93	0.06
Crude fat, %	7.97	9.14	9.22	10.53	0.96	0.04
Crude protein, %	31.96	32.65	32.46	31.98	0.03	NS
Crude fiber, %	9.17	7.76	10.08	6.50	- 0.51	NS
Ash, %	2.58	3.58	3.72	4.62	0.97	0.03
Lysine, %	1.04	1.05	1.09	1.04	0.02	NS
Methionine, %	0.63	0.64	0.59	0.62	- 0.13	NS
Cystine, %	0.61	0.61	0.53	0.62	0.16	NS
Threonine, %	1.20	1.22	1.20	1.20	- 0.18	NS
Phosphorus, %	0.53	0.66	0.77	0.91	0.99	0.002
TME_n, kcal/kg	2712	2897	3002	3743	0.94	0.06
Lys digestibility, %	78.2	76.0	69.7	75.0	- 0.90	NS
Met digestibility, %	90.9	88.6	86.3	87.3	- 0.92	NS
Cys digestibility, %	87.2	87.6	80.7	80.3	- 0.95	NS
Thr digestibility, %	85.9	83.2	80.5	77.3	- 0.99	0.02
Arg digestibility, %	92.1	90.7	86.7	88.5	- 0.99	0.07

Source: Noll, Parsons, and Walters, 2006.

[a] L* = lightness of color (0 = black, 100 = white). The higher the a* and b* values, the higher the amount of redness and yellowness, respectively.



Source: Ergul et al., 2003.

Figure 10.1. Regression of digestible lysine (%) and color (L*, b*)

Cromwell, Herkleman, and Stahly (1993) evaluated the relationship between Hunter Lab color scores of various sources of DDGS and the content of acid detergent insoluble nitrogen and growth performance of pigs (Table 10.8). They fed a blend of the three darkest DDGS sources and a blend of the three lightest-colored DDGS sources to chicks and pigs and showed that, in both cases, feeding the blend of the darkest DDGS sources resulted in a reduced rate and efficiency of gain compared to feeding the blend of the lightest-colored sources. They concluded that rate and efficiency of gain are correlated with the color of the DDGS, as well as the concentrations of crude protein, lysine, sulfur amino acids, acid detergent insoluble nitrogen, and acid detergent fiber in DDGS.

Urriola (2007) showed that the lysine content ranged from 0.52% to 1.13% and the standardized true ileal lysine digestibility ranged from 17.7% to 74.4% among 34 different DDGS sources. Because of our need to know the amino acid digestibility for swine and poultry, which varies among DDGS sources, current research is evaluating the accuracy of several in vitro laboratory procedures to predict these values before formulating and manufacturing diets.

It is likely that much of the difference in lysine digestibility among DDGS sources is due to drying time and temperature used. Dryer tem-

Table 10.8. Effect of acid detergent insoluble nitrogen (ADIN) and color score on growth performance of pigs fed three blended sources of distillers dried grains with solubles

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			

Source: Cromwell, Herkleman, and Stahly, 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 the amount of redness and yellowness, respectively.

peratures can range from 260° to 1150° F, depending on the ethanol plant. Since the amount of heat and length of heating time are highly correlated to lysine digestibility, it is not surprising that a fairly wide range of lysine digestibility exists among DDGS sources.

Availability of Phosphorus in Distillers Dried Grains with Solubles

The phosphorus content of DDGS is approximately 0.75% on a dry matter basis, which is three times greater than that of corn. In corn, only 14% of the total phosphorus is digestible for swine, but the apparent total tract phosphorus availability is increased to approximately 59% after fermentation (Pedersen, Boersma, and Stein, 2007). The phosphorus digestibility in DDGS corresponds to availability values between 70% and 90% relative to those for dicalcium phosphate. Therefore, with DDGS inclusion in swine diets, the utilization of organic phosphorus will increase, which in turn will reduce the need for supplemental inorganic phosphorus (i.e., dicalcium phosphate or monocalcium phosphate). However, Xu et al. (2006a,b) and Xu, Whitney, and Shurson (2006a) showed that feeding diets containing DDGS reduces the concentration of phosphorus in manure; dry matter digestibility is also reduced, and fecal excretion (manure volume) is increased in nursery pigs but not in growing-finishing pigs (Xu, Whitney, and Shurson, 2006b). The net result is a slight reduction or no change in total phosphorus excretion in manure with DDGS inclusion.

Similarly, the phosphorus availability in DDGS is also high for poultry diets; it was estimated to be between 54% and 68% (Lumpkins and Batal, 2005). Comparing different DDGS sources, Martinez Amezcua, Parsons, and Noll (2004) obtained bioavailability estimates for phosphorus of 69%, 75%, 82%, and 102%, suggesting that phosphorus availability varies among DDGS sources, but DDGS provide an excellent source of available phosphorus for poultry diets.

Presence of Potential Contaminants or Antinutritional Factors

Mycotoxins

Mycotoxins can be present in corn co-products if the grain delivered to the ethanol plant is contaminated. Mycotoxins are not destroyed during the ethanol production process or the drying process to produce corn co-products. However, the risk of mycotoxin contamination is very low because many ethanol plants monitor grain quality and reject sources that may be contaminated with mycotoxins.

When samples of corn co-products are tested, only high-performance liquid chromatography (HPLC) should be used. For mycotoxins, HPLC is the detection reference method for DDGS. Many test kit products based on Enzyme-Linked ImmunoSorbent Assay initially developed for basic commodities such as corn and wheat are known to provide incorrect, false positive readings and elevated mycotoxin levels when used with DDGS and should be avoided. These kits are established and developed to accurately detect mycotoxins in grains but not in DDGS. The difference is likely due to interferences by compounds unique to DDGS but not to whole grain.

To accurately detect mycotoxins and determine their level in DDGS, careful and methodical sampling procedures must be followed. This is because mycotoxins can be present in isolated parts of a grain or grain co-product container or truck, in very small quantities (parts per million or billion [ppb]). For example, one sample collected from a truck or a container could contain >100 ppb, with a different sample collected from the same truck being non-detectable (< 1 ppb). Therefore, it is extremely important to collect multiple small samples from each load or shipment rather than one large sample.

Sulfur

Distillers grains with and without solubles can sometimes be high in sulfur and contribute significant amounts of sulfur to the diet. If more than 0.4% sulfur from feed (dry matter basis) and water is consumed, polioencephalomalacia in cattle can occur. Furthermore, sulfur interferes with copper absorption and metabolism, which is worsened in the presence of molybdenum. Therefore, in geographic regions where high sulfur levels are found in forages and water, the level of DDGS in the diet may need to be reduced (Tjardes and Wright, 2002).

Salt

The sodium content of DDGS can range from 0.01% to 0.48%, averaging 0.11%. Therefore, dietary adjustments for sodium content may be necessary for poultry if the source of DDGS being used contains high levels of sodium in order to avoid potential problems with wet litter and dirty eggs.

Antimicrobial Residues

Virginiamycin is the only FDA-approved antimicrobial additive that can be used in very small quantities to control bacterial infections in fermenters during the ethanol production process. However, there are no antibiotic residues in distillers grains co-products because these antibiotics are destroyed at a temperature of > 200° C in the distillation towers (Shurson et al., 2003). Ethanol plants are encouraged to work with their antibiotic vendors to obtain an annual certified test and to keep the certification on file, demonstrating that no detectable levels of antibiotics are present in corn co-products.

Physical Characteristics of Distillers Dried Grains with Solubles that Affect Quality

Flowability

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, 2006). 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, 2006). 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, 2006). Shear testing equipment is used to measure the strength and flow properties of bulk materials. It is also used to measure the amount of compaction as well as the bulk strength of materials (Rosentrater, 2006). Another approach for assessing 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, 2006).

Unfortunately, DDGS can have some very undesirable handling characteristics related to poor flowability under certain conditions (AURI and Minnesota Corn Growers Assoc., 2005). Reduced flowability and bridging of DDGS in bulk storage containers and transport vehicles limit the acceptability of DDGS for some suppliers because customers (feed mills) do not want to deal with the inconvenience and expense of handling a feedstuff that does not flow through their milling systems.

Very few studies have attempted to characterize factors that affect flowability of DDGS. The Agricultural Utilization Research Institute (AURI) and the Minnesota Corn Growers Association (2005) studied a limited number of DDGS samples under laboratory conditions. They reported that relative humidity greater than 60% seemed to reduce flowability of a DDGS sample, which is likely due to the product's ability to absorb moisture. Besides the relative humidity, other suggested factors that may affect DDGS flowability include particle size, content of solubles, dryer temperature, and moisture content at dryer exit.

Johnston et al. (2007) conducted an experiment at a commercial dry-grind ethanol plant to determine if selected additives would improve flowability of DDGS. The treatments consisted of moisture content of DDGS (9% vs. 12%) and flowability additive treatments: no additive (control); a moisture migration control agent at 2.5 kg/metric ton (DMX-7, Delst, Inc.); calcium carbonate at 2% (calcium carbonate, Unical-P, ILC

Resources); or a clinoptilolite zeolite at 1.25% (zeolite, St. Cloud Mining Co.). The flowability additives were included at the desired level to about 2,275 kg of DDGS using a vertical-screw feed mixer and augered into truck compartments. The time required to unload each compartment was recorded. The flow rate of DDGS at unloading was higher for the 9% compared with 12% moisture level (620 vs. 390 kg/min). The flow rates of DDGS at unloading were 509 (control), 441 (DMX-7), 512 (calcium carbonate), and 558 (zeolite) kg/min. None of the flowability additives created flow rates that differed significantly from the control.

Color

As mentioned earlier, the color of DDGS can vary from very light golden yellow to very dark brown and is commonly measured in the laboratory using either Hunter Lab or Minolta colorimeters. These methods 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, Herkleman, and Stahly, 1993). This system measures lightness (L* reading; 0 = dark, 100 = light), redness (a* reading), and yellowness (b* reading) of color. Color differences among DDGS sources are due to the amount of solubles added to grains before drying, the type of dryer and drying temperature, and the natural color of the feedstock grain being used.

The color of corn kernels can vary among varieties and has some influence on the 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 is added to the mash (grains fraction) to make DDGS, the color becomes darker. Noll, Parsons, and Walters (2006) evaluated the color of DDGS batches prepared with approximately 0%, 30%, 60%, and 100% of the maximum possible amount of syrup added to the mash before drying (corresponding to 0, 12, 25, and 42 gallons/minute of solubles). As shown in Table 10.9, increasing the solubles addition rate to the mash resulted in a decrease in L* (lightness) and b* (yellowness), with an increase in a* (redness). Similar results were also reported by Ganesan, Rosentrater, and Muthukumarappan (2005).

Table 10.9. The effect of the rate of solubles addition to mash on color characteristics of distillers dried grains with solubles

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

Source: Adapted from Noll, Parsons, and Walters, 2006.
[a] L* = lightness of color (0 = black, 100 = white). The higher the a* and b* values, the higher the amount of redness and yellowness, respectively.

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 of the Maillard reaction in foods, which affects amino acid digestibility, especially for lysine. Lightness and yellowness of DDGS color appear to be reasonable predictors of digestible lysine content for poultry (Ergul et al., 2003) and swine (Cromwell, Herkleman, and Stahly, 1993; Pederson, Pahm, and Stein, 2005).

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 use fewer enzymes, while other plants 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 affect final nutrient composition and digestibility.

Smell

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

Bulk Density, Particle Size, and pH

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

Table 10.10. Particle size, bulk density, and pH of 34 sources of distillers dried grains with solubles

	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

Source: Shurson, 2005 (unpublished data).

particles settle to the bottom of a load during transport, whereas low bulk density particles rise to the top of a load.

Samples of DDGS were collected by researchers at the University of Minnesota (unpublished data) in 2004 and 2005 (34 samples from ethanol plants in 11 different states). As shown in Table 10.10, average particle size was 665 μm but particles had an extremely large range, from 256 to 1087 μm. The pH of DDGS sources averages 4.1 but can range from 3.6 to 5.0.

Pelleting

The high fiber and fat content of DDGS makes it difficult to produce a firm pellet with minimal fines using conventional pelleting processes. Furthermore, adding DDGS to swine and poultry diets reduces the throughput of pellet mills.

Shelf Life

Preservatives and mold inhibitors are commonly added to wet distillers 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. There are no published data demonstrating that preservatives and mold inhibitors are necessary to prevent spoilage and extend shelf life of DDGS.

Unless the moisture content exceeds 12% to 13%, the shelf life of DDGS appears to be stable for many months. In a field trial performed by the U.S. Grains Council, a sample of DDGS was shipped from an ethanol plant in South Dakota in a 40-foot container to Taiwan. Upon arrival, the DDGS sample was placed into 50 kg bags and stored in a covered steel pole barn for ten weeks during the course of the dairy feeding trial on a commercial dairy farm located about 20 km south of the Tropic of Cancer. Environmental temperatures averaged more than 32 °C and humidity was in excess of 90% during this storage period. There was no change in peroxide value (measure of oxidative rancidity of oil) in samples collected at arrival and again after the ten-week storage period, presumably because of the high amount of natural antioxidants present in corn, which are further increased by the heating process (Adom and Liu, 2002; Dewanto, Wu, and Liu, 2002).

Hygroscopicity

Limited information exists regarding the hygroscopicity, or ability to attract moisture, of DDGS. However, the U.S. Grains Council sponsored a broiler field trial in Taiwan, in which moisture content of DDGS was monitored during storage at a commercial feed mill from March to June of 2004. A random sample of DDGS was obtained weekly from storage at the feed mill and analyzed for moisture over a thirteen-week storage period. Moisture content increased from 9.05% at the beginning to 12.26% at the end of the thirteen-week storage period. Therefore, it appears that under humid climatic conditions, the moisture content of DDGS will increase during long-term storage.

Potential for Improving Quality and Consistency of Corn Co-products

One reason nutrient content is so variable in corn co-products is that different laboratories use different analytical methodologies. As a result of this industry-wide problem, the American Feed Ingredient Association, Renewable Fuels Association, and National Corn Growers Association evaluated and published the most appropriate methods for analyzing moisture, crude protein, crude fat, and crude fiber in DDGS in 2007 (Table 10.11).

Summary of Quality Characteristics of Distillers Dried Grains with Solubles

There are many factors that influence DDGS quality. Variability in nutrient content of DDGS appears to be primarily attributable to the inherent variation in nutrient content of corn and the amount of solubles added to the grains fraction. Nutrient digestibility is also affected by the amount of solubles added to the grains when producing DDGS, but the dryer type, time, and temperature have a significant impact on the heat damage to

Table 10.11. American Feed Ingredient Association analytical method recommendations for moisture, crude protein, crude fat, and crude fiber in distillers dried grains with solubles

Analyte	Method	Method Description
Moisture	NFTA 2.2.2.5	Lab dry matter (105° C / 3 hrs.)
Crude protein	AOAC 990.03 [a]	Crude protein in animal feed – combustion
	AOAC 2001.11[a]	Crude protein in animal feed and pet food (copper catalyst)
Crude fat	AOAC 2001.11	Oil in cereal adjuncts (petroleum ether)
Crude fiber		Crude fiber in animal feed and pet food (F.G. crucible)

[a]Methods are statistically similar, and either is acceptable for use on DDGS.

protein—and the resulting reduction in amino acid digestibility. Color, particularly lightness and yellowness, has been shown to be a reasonable predictor of amino acid digestibility, especially for lysine.

Sulfur and sodium (salt) can vary substantially among DDGS sources because of the use of small amounts of chemicals containing these compounds during the ethanol production process. As a result, sulfur and salt levels should be monitored and diet formulation adjustments should be made when DDGS contains high levels of these minerals for cattle and poultry, respectively. Although the prevalence of mycotoxins in DDGS is very low, if mycotoxin-contaminated corn is used to produce ethanol and DDGS, these mycotoxins will still be present and concentrated by about three times the initial level found in corn. Virginiamycin is the only FDA-approved antimicrobial for ethanol production and is used in very small amounts to control bacterial infections in fermenters. Because of the chemical nature of this antimicrobial compound and the high temperature during the DDGS production process, there are no detectable residues in DDGS.

Particle size, bulk density, color, smell, and flowability can vary among DDGS sources and thus are part of the quality characteristics. Based on limited field trials, DDGS appear to be very stable under extreme climate conditions of high temperatures and humidity for at least two to three months without oxidative rancidity of fat. However, because the chemical characteristics of DDGS cause the grains to attract moisture, moisture content can increase slightly over a two- to three-month storage period.

Many fuel ethanol plants have implemented extensive quality control procedures to improve the nutritional and economical values of the produced DDGS. The feed and ethanol industries have also published analytical procedures they recommend for determining moisture, crude protein, crude fat, and crude fiber for DDGS, which will promote more uniform comparisons of levels of these nutrients among sources.

New Fractionation Technologies = New Corn Co-products

Fractionation of corn kernels into different components has been utilized to produce various industrial and food-grade products for many years. More recently, corn fractionation technologies are being developed, evaluated, and implemented by some ethanol plants in an attempt to remove non-fermentable components of the corn kernel and improve ethanol yield. There are several advantages of using fractionation technologies to produce ethanol and new corn co-products:

- A higher percentage of starch entering the ethanol fermentation tanks increases ethanol yield by approximately 10%.
- Fewer enzymes can be used for ethanol production because there is less interference between the oil- and starch-digesting enzymes during fermentation if the corn germ (the portion of the corn kernel containing oil) is removed prior to fermentation.
- There is less co-product mass to dry at the end of the ethanol production process, resulting in lower drying costs and potentially less heat damage to proteins.
- Less energy and water is needed to produce ethanol and corn co-products.
- Oil extraction from the corn germ reduces the need for frequent cleaning of the system, and the high-value oil can be sold or used for other applications such as biodiesel production.
- An increase in the number of fractionated co-products may add value and provide more diversified markets for the co-products.

Adoption of these technologies is being accelerated to increase ethanol yield from a bushel of corn because of increased demand and cost of corn, high natural gas prices, and the potential for reduced capital costs by implementing fractionation technologies. Furthermore, some ethanol plants desire a more diversified portfolio of corn co-products to target specific markets.

The Basics of Fractionation

Fractionation involves separating the corn kernel into three components: the endosperm, germ, and bran (tip and pericarp). The endosperm represents about 83% of the corn kernel and is primarily composed of starch, whereas the germ (about 12% of the kernel) is high in oil, protein, ash, and non-fermentable carbohydrates. The remaining bran portion is almost exclusively composed of fiber (non-fermentable carbohydrates).

There are a number of fractionation technologies being developed, but they have not yet become a significant part of ethanol and co-product production. These technologies can be divided into two categories:

- Front-end fractionation
  This involves separating the endosperm, germ, and bran fractions before fermentation. The endosperm fraction (rich in starch) is fermented to produce ethanol and a corn co-product. Corn oil is extracted from the germ fraction and marketed or utilized for various industrial applications, leaving the corn germ meal as a feed co-product. The bran fraction is also separated and used as a high-fiber feed, primarily for ruminants.

- Back-end fractionation
  This involves a two-step process to extract corn oil after the entire corn kernel is fermented to produce ethanol. Crude corn oil is extracted from thin stillage, resulting in low-fat syrup, which undergoes a second extraction along with whole stillage to separate more corn oil. The remaining residue is used to produce low-fat distillers grains.

General Nutrient Composition of New Fractionated Corn Co-products

Because fractionation is a new and emerging technology in fuel ethanol production, there are limited nutrient composition data for the resulting co-products. Dry matter, crude protein, crude fat, crude fiber, and ash concentrations for most of the known fractionated co-products are shown in Table 10.12.

In general, most fractionated corn co-products are higher in crude protein and crude fiber than DDGS and are lower in crude fat. Although

Table 10.12. Nutrient composition (%) of new fractionated corn distillers co-products (dry matter basis)

Company Co-product	Dry Matter	Crude Protein	Crude Fat	Crude Fiber	Ash
Typical corn DDGS	89.3	30.9	10.7	7.2	6.0
Poet Dakota Gold HP	91.6	44.8	3.9	7.3	2.1
Poet Dakota Bran	ND[a]	14.6	9.8	3.8	4.6
Poet Dehydrated Corn Germ	93.2	16.9	18.9	5.5	5.8
Maize Processing Innovators Quick Germ/Quick Fiber DDGS	ND	49.3	3.9	6.8	3.2
Maize Processing Innovators E-Mill DDGS	ND	58.5	4.5	2.0	3.2
Cereal Process Technologies Hi-Protein DDGS	ND	35.0-37.0	4.0-6.0	4.0-6.0	ND
Renessen Enhanced DDGS	ND	40.0-50.0	2.5-4.0	7.0-11.0	ND
Solaris NeutraGerm	97.0	17.5	45.0	6.0	1.9
Solaris Probran	90.0	9.5	2.0	16.6	1.0
Solaris Glutenol	90.0	45.0	3.3	3.8	4.0
Solaris Energia	90.0	30.0	2.5	8.2	2.5
FWS Technologies Enhanced DDGS	ND	35.0-37.0	6.5	ND	3.8
De-Oiled DDGS	89.9	31.3	2.3	ND	6.2
J. Jireh Products Dried Condensed Solubles	93.4	21.6	4.7	3.1	8.3

[a]ND = not determined.

the amino acid concentration may increase somewhat in many of these high-protein fractionated co-products, the protein quality (amino acid balance) is still poor relative to the requirements of monogastric animals. The reduced fat and increased fiber content of these fractions may result in lower energy value for swine and poultry. Therefore, their feeding and economic value may be reduced compared to DDGS for swine and poultry. However, the nutrient composition of these co-products would likely have greater value in ruminant diets because amino acid balance of corn protein is not as critical for ruminants as it is for swine and poultry. Furthermore, the increased amount of readily fermentable fiber can provide a good source of energy, and the lower fat content may allow higher dietary inclusion rates for lactating dairy cows while avoiding concerns of milk fat depression.

Potential Feeding Value of New Fractionated Corn Co-products for Livestock and Poultry

Because most of the new fractionation technologies have not been fully implemented and are being evaluated, limited quantities of fractionated corn co-products are being produced and are available commercially. As a result, there are limited published data on the efficiency and quality of these fractionated corn co-products in livestock and poultry feeds. Until such data become available, it is difficult to determine the comparative feeding values, dietary inclusion rates, and comparative nutritional and economic values of these co-products.

The following is a summary of recent studies conducted to evaluate selected fractionated co-products for various farm animal species.

Poultry. A high-protein hydrolyzed corn co-product obtained from the National Renewable Energy Laboratory was evaluated for nutrient content and digestibility, and for its feeding value in turkey starter diets (Abe et al., 2004). Dry matter, ash, fat, fiber, protein, starch, and sugar content were 95.9%, 1.43%, 10.7%, 3.9%, 57.8%, 1.6%, and 2.0%, respectively. The lysine, arginine, tryptophan, threonine, cystine, and methionine content as a percentage of crude protein were 1.99%, 2.63%, 0.34%, 3.14%, and 2.1%, respectively, and digestibility coefficients were 68.1%, 79.0%, 64.0%, 75.2%, 78.3%, and 85.9%, respectively. The nitrogen-corrected true metabolizable energy (TME_n) was 2,692 kcal/kg on an as-fed basis. When 0%, 5%, 10%, 15%, and 20% of this co-product were added to the diets and fed from three to eighteen days of age, there was a linear decrease in the average daily gain at day eleven, and a cubic effect from day eleven to eighteen. These results suggest that up to 10% of this co-product can be used effectively up to day fourteen, and higher inclusion rates may provide satisfactory growth for turkeys older than two weeks.

Batal (2007) determined the nutrient digestibility of DDGS, high protein distillers dried grains with solubles (HP-DDGS), dehydrated corn germ, and bran for poultry; the results are shown in Table 10.13. These results indicate that new fractionation technologies used in ethanol pro-

Table 10.13. Nutrient content and digestibility of distillers dried grains with solubles, high protein distillers dried grains with solubles, dehydrated corn germ, and corn bran for poultry

Nutrient	DDGS	HP-DDGS	Dehydrated Corn Germ	Bran Cake
Crude protein, %	27.0	44.0	15.5	11.6
Crude fiber, %	7.0	7.0	4.5	4.5
Crude fat, %	10.0	3.0	17.0	7.8
TME_n, kcal/kg	2,829	2,700	2,965	2,912
Lysine, %	0.79	1.03	0.83	0.43
Lysine availability, %	81	72	80	68
Lysine as a % of CP	2.9	2.3	5.4	3.7
Phosphorus, %	0.77	0.35	1.18	No data
P bioavailability, %	60	47	31	No data

Source: Batal, 2007.

duction result in co-products that have unique nutritional properties, and knowledge of their nutritional value is essential in order to assess their economic and feeding value.

HP-DDGS (33% protein, 0.33% phosphorus on a 90% dry matter basis) and corn germ meal (14% crude protein and 1.22% phosphorus) were fed to chicks and precision-fed roosters to determine the TME_n, amino acid digestibility, and phosphorus bioavailability for poultry (Kim et al., 2008). The TME_n and amino acid digestibility in corn germ meal were significantly higher compared to HP-DDGS, while phosphorous bioavailability was similar between DDGS and HP-DDGS (60% vs. 58%, respectively) but lower for corn germ meal (25%). These results suggest that corn germ meal is a better source of energy, with higher amino acid digestibility than high HP-DDGS, but DDGS and HP-DDGS are better sources of bioavailable phosphorus than is corn germ meal for poultry.

Swine. Widmer, McGinnis, and Stein (2007) conducted three experiments to determine energy, phosphorus, and amino acid digestibility in high protein distillers dried grains (without solubles) (HP-DDG) and corn germ compared to corn. The digestible and metabolizable energy content of corn (4,056 and 3,972 kcal/kg of dry matter, respectively) was similar to that in corn germ (3,979 and 3,866 kcal/kg, respectively) but was surprisingly lower than that in HP-DDG (4,763 and 4,476 kcal/kg, respectively). True total tract digestibility of phosphorus was higher in HP-DDG (69%) compared to corn germ (34%), similar to values obtained by Kim et al.

(2008) in poultry. Standardized ileal digestibilities for crude protein and all amino acids except arginine, lysine, glycine, and proline were higher in HP-DDG than in corn germ. Therefore, HP-DDG has higher levels of digestible energy, phosphorus, and most amino acids than does corn germ for swine.

Widmer et al. (2008) also evaluated the effects on growth performance, carcass quality, and palatability of pork of feeding DDGS (10% or 20% of the diet), HP-DDG (replaced 50% or 100% of soybean meal), and corn germ (5% or 10% of the diet) to growing-finishing pigs. Results from this study showed that feeding diets containing 20% DDGS or high dietary inclusion rates of HP-DDG had no negative effect on growth performance, carcass composition, muscle quality, or eating characteristics of bacon and pork chops but it may decrease pork fat quality. Similarly, feeding diets containing up to 10% corn germ had no negative effects on growth performance, carcass composition, carcass quality or eating characteristics of bacon and pork loins but increased final body weight and improved bacon fat quality (reduced iodine value).

Stein et al. (2005) conducted two studies to determine the digestibility of energy, crude protein, and amino acids from a yeast product extracted from ethanol co-product streams. The concentration of digestible and metabolizable energy in the yeast product was 5,600 and 5,350 kcal/kg of dry matter, respectively, which is 138% to 134% of the value found in corn (4,071 and 3,992 kcal/kg, respectively). The standardized ileal digestibility coefficients were also high for crude protein (74.8%), lysine (82.2%), methionine (88.6%), threonine (71.1%), tryptophan (82.2%), isoleucine (79.5%), leucine (84.0%), and valine (74.5%). These results suggest that this yeast product can be an excellent source of energy and digestible amino acids in swine diets.

Dairy. Kelzer et al. (2007) conducted a study to determine protein fractions and evaluate differences in rumen undegradable protein (RUP), RUP digestibility (dRUP), and amino acid concentrations in corn germ, corn bran, HP-DDGS, two sources of DDG, wet corn gluten feed, and wet distillers grains. A comparison of the nutrient concentrations in these corn by-products is shown in Table 10.14. Concentrations of RUP, dRUP, lysine, and methionine were different among corn milling co-product sources.

Table 10.14. Comparison of protein fraction concentrations as a percentage of crude protein among seven corn milling co-products

Protein fraction, % CP	Corn Germ	Corn Bran	High Protein DDGS	DDGS 1	DDGS 2	Wet Corn Gluten Feed	Wet Distillers Grains
Crude protein, % DM	16.3	13.5	47.2	30.1	28.9	26.7	29.9
Non-protein nitrogen	30.0	33.5	7.4	17.0	17.9	36.6	18.6
Rapidly degradable true protein	15.0	4.0	0.6	7.0	2.1	15.9	2.4
Moderately degradable true protein	38.1	54.3	82.4	67.0	41.0	33.2	53.1
Slowly degradable true protein	13.5	6.0	8.8	4.8	11.1	10.1	11.0
Undegraded true protein	3.4	2.2	0.8	4.2	27.9	4.1	14.9
Rumen undegraded protein	16.5	20.7	55.2	33.2	56.3	11.5	44.7
RUP digestibility	66.8	65.8	97.7	92.0	91.9	51.0	93.1
Lysine	2.9	3.2	2.0	1.9	1.9	3.5	1.9
Methionine	1.9	1.4	3.2	2.0	2.4	1.6	2.3

Source: Kelzer et al., 2007.

Corn germ produced as a co-product from ethanol production has been evaluated as an energy supplement for lactating dairy cows (Abdelqader et al., 2006). All diets contained a 5-to-45 forage-to-concentrate ratio, whereby forage was 60% corn silage and 40% alfalfa hay, and the concentrate contained 0%, 7%, 14%, or 21% of diet dry matter as corn germ. The addition of corn germ had no effect on dry matter intake, but increased concentrations of corn germ resulted in a quadratic response for milk yield, energy-corrected milk, milk fat concentration, and milk fat yield. Milk fat yield decreased when cows were fed the diet containing 21% corn germ meal, and milk protein content decreased linearly with increased corn germ in the diet, but milk protein yield and feed efficiency were not affected. These results suggest that adding corn germ at 7% and 14% of diet dry matter will increase milk and milk fat yield, but at the 21% level the concentration of milk fat will decrease.

Janicek et al. (2007) evaluated the effects of 10%, 17.5%, and 25% corn bran (replacing a portion of corn silage and alfalfa on a dry matter basis) on milk yield of lactating dairy cows. Moisture, crude protein, neutral detergent fiber, nonfiber carbohydrate, ether extract, and phosphorus content of the corn bran were 8.2%, 12.9%, 30.4%, 45.0%, 9.9%, and 0.70%, respectively. When corn bran increased from 10% to 25%, there were no effects on dry matter intake or milk fat yield, but milk yield, milk protein yield, and feed conversion all increased. The decrease in milk fat concentration with increasing levels of corn bran, coupled with the increase in total milk yield, resulted in no differences between dietary treatments in 3.5% fat-corrected milk.

Beef. Bremer et al. (2006) evaluated a low-protein corn co-product called Dakota Bran Cake (DBRAN) on feedlot performance and carcass characteristics for finishing cattle. Diets contained 0%, 15%, 30%, or 45% DBRAN or 30% DDGS, replacing corn on a dry matter basis. Final body weight, average daily gain, and feed conversion increased linearly, and daily dry matter intake responded in a positive quadratic manner as the level of DBRAN increased in the diet. There were no differences among dietary treatments in carcass characteristics except for a linear increase in hot carcass weight for steers fed increasing levels of DBRAN. These results suggest that feeding DBRAN at up to 45% of the diet improves growth performance with no effects on carcass characteristics, and that DBRAN has approximately 100% to 108% of the energy value of corn.

DDGS from a traditional dry-grind ethanol production process was compared to DDGS obtained from a partial fractionation process at a level of 13% of the diet on a dry matter basis (Depenbusch et al., 2008). No differences in dry matter intake, average daily gain, gain efficiency, or carcass characteristics were observed for heifers fed either diet, but those fed the traditional DDGS diet consumed more feed. These results suggest that moderate inclusion levels of DDGS in flaked corn diets for finishing heifers can provide satisfactory growth performance and carcass characteristics.

Summary: Use of Fractionated Corn Co-products in Livestock Feed

Corn fractionation has been used for many years to produce specialized industrial and food-grade products. In order to minimize cost and improve ethanol yields, fuel ethanol plants are beginning to implement "front-end" processes to separate the endosperm (starch-rich fraction) from the non-fermentable fractions, including the germ and bran. "Back-end" fractionation technologies are used to extract corn oil from the co-product streams, resulting in higher protein and fiber but lower oil content of the resulting feed ingredient co-products. The number of published scientific studies that evaluate these fractionated corn co-products in livestock and poultry feeds has been limited. Until more research is conducted, it is difficult to determine the co-products' comparative feeding value, dietary inclusion rates, and comparative nutritional and economic value. However, all of the fractionated co-products produced have nutritional value and feeding applications in animal feeds.

References

Abdelqader, M., A.R. Hippen, D.J. Schingoethe, K.F. Kalscheur, K. Karges, and M.L. Gibson. 2006. "Corn Germ from Ethanol Production as an Energy Supplement for Lactating Dairy Cows." *J. Dairy Sci.* 89(Suppl. 1): 156.

Abe, C., N.J. Nagle, C. Parsons, J. Brannon, and S.L. Noll. 2004. "High Protein Corn Distiller Grains as a Feed Ingredient." *J. Anim. Sci.* 82(Suppl. 1): 264.

Adom, K.K., and R.H. Liu. 2002. "Antioxidant Activity of Grains." *J. Agric. Food Chem.* 50: 6182-6187.

Agricultural Utilization Research Institute (AURI), and Minnesota Corn Growers Association. 2005. *Distiller's Dried Grains Flowability Report.* Waseca, MN.

Batal, A. 2007. "Nutrient Digestibility of High Protein Corn Distillers Dried Grains with Solubles, Dehydrated Corn Germ and Bran." 2007 ADSA/ASAS/AMPA/PSA joint annual meeting, San Antonio, TX. July 8-12. Abstract M206.

Bremer, V.R., G.E. Erickson, T.J. Klopfenstein, M.L. Gibson, K.J. Vander Pol, and M.A. Greenquist. 2006. "Evaluation of a Low Protein Distillers By-product for Finishing Cattle." *Nebraska Beef Report,* pp. 57-58.

Cromwell, G.L., K.L. Herkleman, and T.S. Stahly. 1993. "Physical, Chemical, and Nutritional Characteristics of Distillers Dried Grains with Solubles for Chicks and Pigs." *J. Anim. Sci.* 71: 679-686.

Depenbusch, B.E., E.R. Loe, M.J. Quinn, M.E. Corrigan, M.L. Gibson, K.K. Karges, and J.S. Drouillard. 2008. "Corn Distiller's Grain with Solubles Derived from a Traditional or Partial Fractionation Process: Growth Performance and Carcass Characteristics of Finishing Feedlot Heifer." *J. Anim. Sci*. 1910. doi: 10.2527/jas.2007-0501.

Dewanto, V., X. Wu, and R.H. Liu. 2002. "Processed Sweet Corn Has Higher Antioxidant Activity." *J. Agric. Food Chem.* 50: 4959-4964.

Ergul, T., C. Martinez Amezcus, C.M. Parsons, B. Walters, J. Brannon and S.L. Noll. 2003. "Amino Acid Digestibility in Corn Distillers Dried Grains with Solubles." *Poultry Sci.* 82(Suppl. 1): 70.

Ferrer, E., A. Algria, Farré, G. Clemente, and C. Calvo. 2005. "Fluorescence, Browning Index, and Color in Infant Formulas During Storage." *J. Agric. Food Chem*. 53: 4911-4917.

Ganesan, V., K.A. Rosentrater, and K. Muthukumarappan. 2005. "Effect of Moisture Content and Soluble Levels on the Physical and Chemical Properties of DDGS." ASAE Paper No. 056110. American Society of Agricultural and Biological Engineers, St. Joseph, MI.

Janicek, B.N., P.J. Kononoff, A.M. Gehman, K. Karges, and M.L. Gibson. 2007. "Effect of Increasing Levels of Corn Bran on Milk Yield and Composition." *J. Dairy Sci.* 90: 4313-4316.

Johnston, L.J., A.M. Hilbrands, G.C. Shurson, and J. Goihl. 2007. "Selected Additives Do Not Improve Flowability of Dried Distillers Grains with Solubles (DDGS) in Commercial Systems." *J. Anim. Sci.* 86(e-Suppl. 3): 54.

Kelzer, J.M., P.J. Kononoff, K. Karges, and M.L. Gibson. 2007. "Evaluation of Protein Fractionation and Ruminal and Intestinal Digestibility of Corn Milling Co-products." Dakota Gold Research Association. http://www.dakotagold.org/research/dairy.asp (downloaded June 24, 2008).

Kim, E.J., C. Martinez Amezcua, P.L. Utterback, and C.M. Parsons. 2008. "Phosphorus Bioavailability, True Metabolizable Energy, and Amino Acid Digestibilities of High Protein Corn Distillers Dried Grains and Dehydrated Corn Germ." *Poultry Sci.* 87: 700-705.

Knott, J., G.C. Shurson, and J. Goihl. 2004. "Effects of the Nutrient Variability of Distiller's Solubles and Grains within Ethanol Plants and the Amount of Distiller's Solubles Blended with Distiller's Grains on Fat, Protein and Phosphorus Content of DDGS." http://www.ddgs.umn.edu/articles-proc-storage-quality/2004-Knott-Nutrientvariability.pdf. (accessed June 2008).

Lumpkins, B.S., and A.B. Batal. 2005. "The Bioavailability of Lysine and Phosphorus in

Distillers Dried Grains with Solubles." *Poultry Sci.* 84: 581-586.

Martinez Amezcua, C., C.M. Parsons, and S.L. Noll. 2004. "Content and Relative Bioavailability of Phosphorus in Distillers Dried Grains with Solubles in Chicks." *Poultry Sci.* 83: 971-976.

Noll, S., C. Parsons, and B. Walters. 2006. "What's New since September 2005 in Feeding Distillers Co-products to Poultry." *Proceedings of the 67th Minnesota Nutrition Conference and University of Minnesota Research Update Session: Livestock Production in the New Millennium,* pp. 149-154.

Olentine, C. 1986. "Ingredient Profile: Distillers Feeds." *Proceedings of the Distillers Feed Conference* 41: 13-24.

Pederson, C., A. Pahm, and H.H. Stein. 2005. "Effectiveness of In Vitro Procedures to Estimate CP and Amino Acid Digestibility Coefficients in Dried Distillers Grain with Solubles by Growing Pigs." *J. Anim. Sci.* 83(Suppl. 2): 39.

Pedersen, C., M.G. Boersma, and H.H. Stein. 2007. "Digestibility of Energy and Phosphorus in 10 Samples of Distillers Dried Grains with Solubles Fed to Growing Pigs." *J. Anim. Sci.* 85: 1168-1176.

Reese, D.E., and A,J. Lewis. 1989. "Nutrient Content of Nebraska Corn." Nebraska Cooperative Extension Service EC 89-219, pp. 5-7.

Rosentrater, K.A. 2006. "Understanding Distiller's Grain Storage, Handling, and Flowability Challenges." *Distiller's Grains Quarterly,* First Quarter, pp. 18-21.

Shurson, J., M.J. Spiehs, J.A. Wilson, and M.H. Whitney. 2003. "Value and Use of 'New Generation' Distiller's Dried Grains with Solubles in Swine Diets." *Proceedings of the 19th International Alltech Conference,* Lexington, KY, May 13.

Spiehs, M.J., M.H. Whitney, and G.C. Shurson. 2002. "Nutrient Database for Distiller's Dried Grains with Solubles Produced from New Ethanol Plants in Minnesota and South Dakota." *J. Anim. Sci.* 80: 2639.

Stein, H.H., M.L. Gibson, M.G. Boersma, and C. Pedersen. 2005. "Digestibility of CP, AA, and Energy in a Novel Yeast Product by Pigs." *J. Anim. Sci.* 83(Suppl. 1): 35.

Stein, H.H., M.L. Gibson, C. Pedersen, and M.G. Boersma. 2006. "Amino Acid and Energy Digestibility in Ten Samples of Distillers Dried Grain with Solubles Fed to Growing Pigs." *J. Anim. Sci.* 84: 853-860.

Tjardes, J., and C. Wright. 2002. "Feeding Corn Distiller's Co-products to Beef Cattle." *Extension Extra,* ExEx 2036, August, South Dakota State University Cooperative Extension Service, Dept. of Animal and Range Sciences, pp. 1-5.

Urriola, P.E. 2007. "Digestibility of Dried Distillers Grains with Solubles, In Vivo Estimation and In Vitro Prediction." M.S. thesis, University of Minnesota.

Urriola, P.E., M.H. Whitney, N.S. Muley, and G.C. Shurson. 2006. "Evaluation of Regional Differences in Nutrient Composition and Physical Characteristics among Six U.S. Soybean Meal Sources." *J. Anim. Sci.* 84(Suppl. 2): 24.

Widmer, M.R., L.M. McGinnis, and H.H. Stein. 2007. "Energy, Phosphorus, and Amino Acid Digestibility of High-Protein Distillers Dried Grains and Corn Germ Fed to Growing Pigs." *J. Anim. Sci.* 85: 2994-3003.

Widmer, M.R., L.M. McGinnis, D.M. Wulf, and H.H. Stein. 2008. "Effects of Feeding Distillers Dried Grains with Solubles, High Protein Distillers Dried Grains, and Corn Germ to Growing-Finishing Pigs on Pig Performance, Carcass Quality, and the Palatability of Pork." *J. Anim. Sci.* 1910. doi: 10.2527/jas.2007-0594.

Xu, G., G. He, S.K. Baidoo, and G.C. Shurson. 2006a. "Effect of Feeding Diets Containing Corn Distillers Dried Grains with Solubles (DDGS), With or Without Phytase, on Nutrient Digestibility and Excretion in Nursery Pigs." *J. Anim. Sci.* 84(Suppl. 2): 91 (Abstr.).

Xu, G., G. He, M. Song, S.K. Baidoo, and G.C. Shurson. 2006b. "Effect of Ca:Available P Ratio on Dry Matter, Nitrogen, Phosphorus, Calcium, and Zinc Balance and Excretion in Nursery Pigs Fed Corn-Soybean Meal Diets Containing DDGS and Phytase." *J. Anim. Sci.* 84(Suppl. 2): 91 (Abstr.).

Xu, G., M.H. Whitney, and G.C. Shurson. 2006a. "Effect of Feeding Diets Containing Corn Distillers Dried Grains with Solubles (DDGS), and Formulating Diets on Total or Available Phosphorus Basis, on Phosphorus Retention and Excretion in Nursery Pigs." *J. Anim. Sci.* 84(Suppl. 2): 91 (Abstr.).

———. 2006b. "Effects of Feeding Diets Containing Corn Distillers Dried Grains with Solubles (DDGS), With or Without Phytase, on Nutrient Digestibility and Excretion in Grow-Finish Pigs." *J. Anim. Sci.* 84(Suppl. 2): 92 (Abstr.).