Chapter 5

Use of Distillers Co-products in Diets Fed to Poultry

Kristjan Bregendahl

Co-products from distillation of cereal grains for alcohol production have been available to poultry and livestock producers for many years. Although the co-products were considered better suited for ruminants because of their relatively high fiber content, Morrison (1954) suggested that chick diets could contain up to 7% or 8% distillers grains and that diets for laying hens could contain up to 10% distillers grains without affecting performance. No adverse effects on growth performance of broiler chicken or egg production of laying hens were detected when diets with up to 20% distillers dried grains with solubles (DDGS) from beverage-alcohol production were fed (Matterson, Tlustohowicz, and Singsen, 1966; Waldroup et al., 1981), although the feed utilization of broilers tended to decrease when 25% corn DDGS was included in the diet (Waldroup et al., 1981). In addition to being a source of protein and energy, distillers grains were especially useful as a source of the water-soluble vitamins before chemical synthesis and commercialization of vitamins (Morrison, 1954; Matterson, Tlustohowicz, and Singsen, 1966).

Since the late 1990s, fuel ethanol production from corn grain has greatly increased, through a fermentation process that is slightly different from those of beverage-alcohol production. As a result, over 98% of the fermentation co-products available today are from fuel-ethanol production using corn grain as a substrate (University of Minnesota, 2008a). Of the 13,074 million bushels (5.93 million metric tons) of corn produced in the United States in 2007 (USDA-ERS, 2008), an estimated 3,200 million bushels (81.3 million metric tons) were used for ethanol production (USDA, 2007). The majority of the fuel-ethanol co-products—solubles and wet (or partially dried) distillers grains—are used in ruminant diets, but an estimated

Kristjan Bregendahl was an assistant professor in the Department of Animal Science at Iowa State University at the time of this writing. He is presently employed by Hy-Line International in Dallas Center, Iowa.

yearly production of 3.2 million metric tons of corn DDGS are available for use in ruminant and non-ruminant diets (University of Minnesota, 2008a).

In general, fuel ethanol from corn is produced by first grinding the corn grain through a hammer mill. Water is then added to make a slurry, to which carbohydrase enzymes are added and pH is adjusted. The slurry may be jet-cooked at temperatures ranging from 90° to 165°C (194° to 329°F) to remove lactic acid bacteria, followed by cooling and addition of enzymes to further convert the starch into glucose ("liquefaction"). The glucose is then fermented into ethanol (ethyl alcohol) and carbon dioxide using yeast (*Saccharomyces cerevisiae*), and the ethanol is removed from the resulting "beer" through distillation and use of molecular sieves (the latter to remove the water from the distillate). After the ethanol is distilled off from the beer, the whole stillage is centrifuged to separate the wet grains (or wet cake) from the thin stillage. The solubles (or syrup) are produced from the thin stillage through evaporation and condensation. Corn DDGS is finally produced by adding some or all of the solubles to the wet grains followed by drying in a rotary-kiln or a ring drier at temperatures ranging between 127° and 621°C (260° and 1,150°F), depending on the ethanol plant. More detailed information about the ethanol production process is available from the U.S. Grains Council (2008).

Depending on the specific ethanol plant, there can be several variations on the ethanol production process: some remove the oil-rich germ and fiber-rich hulls prior to fermentation to improve ethanol yield, some omit the jet-cooking process, some remove the oil from the thin stillage, and so on. These different processing techniques result in different co-products. For instance, removal of the non-fermentable bran, pericarp fiber, and germ from the corn kernels prior to fermentation results in the co-products high-protein distillers dried grains without solubles (HP-DDG) and corn germ. By definition, corn DDGS (International Feed Number 5-02-843) consist of a dried mixture of at least 75% of the solids in the whole stillage (AAFCO, 2007) and therefore include the wet grains and (most of) the solubles. Corn distillers dried grains (DDG) (International Feed Number 5-02-842), however, include only the wet grains (AAFCO, 2007). Hence, corn DDG do not contain the nutrient-rich solubles fraction, resulting in a markedly different nutrient profile than that of corn DDGS.

DDGS contain all the nutrients in corn grain except most of the starch, which has been fermented to ethanol and carbon dioxide. By removing only the starch, the nutrients in corn grain are concentrated about three times in conventionally processed DDGS, which then typically contain about 27% crude protein, 10% oil, and 0.8% phosphorus (Table 5.1). The HP-DDG, resulting from the pre-fermentation fractionation of the corn grain, contain approximately 40% crude protein, whereas the dehydrated corn germ contains 15% crude protein (Table 5.1). The solubles stemming from the fermentation of fractionated corn grain are combined with the corn hulls and sold for use in ruminant feed. DDGS, HP-DDG, and dehydrated corn germ are suitable feed ingredients for poultry and can be included in diets in the same way as corn grain, soybean meal, canola meal, and so forth as long as the nutrient and energy contents are known and the diet is formulated accordingly. There has been little interest in feeding corn DDG to poultry mainly because of the product's high fiber content, but corn DDG use is possible (Morrison, 1954).

Contents and Bioavailability of Nutrients and Energy for Poultry

Energy

In the United States, the nitrogen-corrected metabolizable-energy (ME_n) system is used to determine feed ingredient energy. This measure represents the gross energy of the feed minus the gross energy of the feces and urine, corrected for nitrogen retained in the body (NRC, 1994). True ME_n (TME_n) is determined by taking into account endogenous (i.e., non-feed) energy losses in the feces. Because of the correction for endogenous energy losses, values for TME_n are usually greater than the corresponding apparent ME_n values, although the values approach each other when birds have free access to feed (NRC, 1994). The energy value of DDGS (corn throughout unless noted) has been evaluated using the precision-fed rooster assay, in which a small amount (25 to 30 g) of DDGS is fed to adult male birds after a twenty-four hour fast, and the resultant excreta is collected over a twenty-four- or forty-eight-hour period; endogenous energy losses are estimated from the gross energy of excreta from birds fasted for twenty-four to forty-eight hours (Sibbald, 1976, 1986).

Table 5.1. Chemical composition of corn grain and co-products from fuel-ethanol production (as-fed basis)

Item	Corn Grain[a]	Corn DDGS[b]	Corn HP-DDG[c]	Corn Germ[c]
	%			
Dry matter	89.0	89.0	91.7	91.1
ME_n[d] (kcal/kg)	3,350	2,770[e]	–	–
TME_n[f] (kcal/kg)	3,470	2,851	2,682	3,881
Crude protein	8.5	26.5	39.6	14.9
Ether extract	3.8	10.1	3.6	15.8
Linoleic acid	2.2	–	–	–
Crude fiber	2.2	7.0	7.5	5.1
Neutral detergent fiber	9.63	32.22[g]	22.20	21.10
Acid detergent fiber	2.83	11.90[g]	11.20	7.50
Calcium	0.02	0.07	0.02	0.02
Phosphorus, total	0.28	0.77	0.44	1.35
Phosphorus, non-phytate	0.08	–	–	–
Phosphorus, available	–	0.48	0.26[h]	0.34[h]
Sodium	0.02	0.20	0.13	0.01
Chloride	0.04	–	–	–
Potassium	0.30	0.85	0.43	1.48
Sulfur	0.08	0.84[i]	0.81	0.19
Arginine, total	0.38	1.09	1.41	1.13
Histidine, total	0.23	0.68	1.08	0.42
Isoleucine, total	0.29	0.96	1.35	0.44
Leucine, total	1.00	3.00	5.09	1.04
Lysine, total	0.26	0.73	1.12	0.79
Methionine, total	0.18	0.50	0.93	0.25
Cystine, total	0.18	0.54	1.32	0.36
Methionine + cystine, total	0.36	1.04	2.25	0.61
Phenylalanine, total	0.38	1.31	2.15	0.60
Threonine, total	0.29	0.96	1.53	0.57
Tryptophan, total	0.06	0.21	0.33	0.19
Valine, total	0.40	1.30	1.93	0.67

Note: Because of an appreciable variation in nutrient and energy contents (discussed in the text), diet formulation should be performed with nutrient and energy values specific to the particular co-product sample used.

[a] Data from NRC (1994).

[b] Data from Waldroup et al. (2007) except as noted.

[c] Data from Poet Nutrition (2008) except as noted.

[d] Nitrogen-corrected apparent metabolizable energy.

[e] Data from Roberson et al. (2005).

[f] Nitrogen-corrected true metabolizable energy.

[g] Mean of five samples reported by Fastinger, Latshaw, and Mahan (2006).

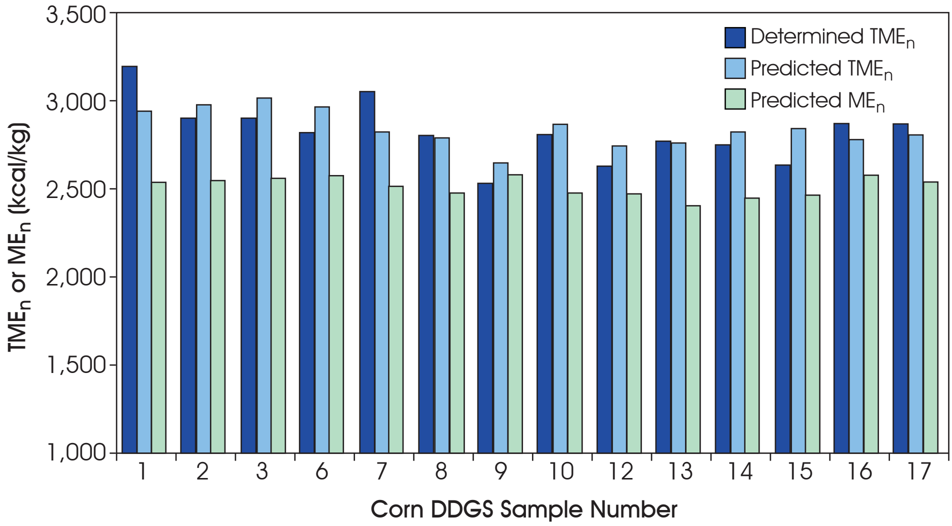
[h] Calculated using bioavailability values of 58% and 25% for corn HP-DDG and corn germ, respectively (Kim et al., 2008).

[i] Data from Batal and Dale (2003).

Lumpkins, Batal, and Dale (2004) reported the TME_n content of a single DDGS sample to be 2,905 kcal/kg. In a later study, the same group determined the TME_n content of 17 different DDGS samples, representing products from six different ethanol plants (Batal and Dale, 2006). The determined TME_n contents ranged from 2,490 to 3,190 kcal/kg with a mean of 2,820 kcal/kg and an associated coefficient of variation of 6.4%. From a smaller data set with five samples of DDGS from five different ethanol plants, Fastinger, Latshaw, and Mahan (2006) concluded that the TME_n content of DDGS averaged 2,871 kcal/kg, albeit with considerable variation among samples (the largest difference in TME_n among the five samples was 563 kcal/kg). A large variation in TME_n values of DDGS was also reported by Parsons et al. (2006), who determined the mean TME_n value of 20 DDGS samples to be 2,863 kcal/kg with a range spanning 447 kcal/kg. Waldroup et al. (2007) suggested that nutritionists use a TME_n value of 2,851 kcal/kg (Table 5.1) for DDGS, based on a survey of published TME_n values. Roberson et al. (2005) determined the apparent ME_n of a single DDGS sample with laying hens to be 2,770 kcal/kg. This value was about 4% lower than the TME_n value determined for the same DDGS sample using cockerels, similar to the relationship between apparent and true ME_n in corn grain (Table 5.1). Roberson (2003) observed that an ME value of 2,870 kcal/kg was too high for DDGS when used in turkey diets and instead used an ME value of 2,805 kcal/kg in a subsequent experiment. This latter apparent ME_n value is 3% less than the TME_n value recommended by Waldroup et al. (2007) (Table 5.1).

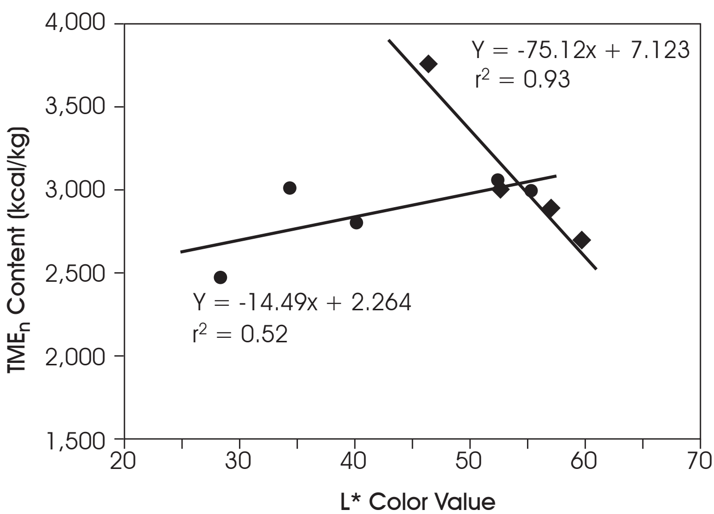
Fastinger, Latshaw, and Mahan (2006) reported both gross energy and TME_n contents (averaging 4,900 and 2,871 kcal/kg, respectively) of five samples of DDGS. These values suggest that the TME_n of DDGS is close to 60% of its gross energy content, similar to the relationship between gross energy and TME_n in other protein-rich ingredients, such as soybean meal (Leske et al., 1991). However, the relationship was decidedly lower (51%) for one sample of DDGS (Fastinger, Latshaw, and Mahan, 2006), so predicting TME_n of DDGS from its gross energy content cannot be recommended, even though gross energy determination is simple, fast, and inexpensive. Rather, the TME_n content can be predicted with better, although not stellar, accuracy from the chemical composition of DDGS. Batal and Dale (2006) correlated the TME_n content of DDGS with its analyzed contents of protein, oil, fiber, and ash, yet the highest coefficient of determination (r^2) was only 0.45. The National Research Council (NRC, 1994) lists ME_n prediction equations for various feed ingredients, including DDGS, based on chemical composition. When the ME_n content of DDGS is calculated by entering the proximate analyses reported by Batal and Dale into the NRC-suggested equation (Figure 5.1), it is evident that the NRC equation underestimates the ME_n content of DDGS when comparing the corresponding TME_n determined by Batal and Dale, even taking into consideration that ME_n values of DDGS are about 4% to 5% lower than their corresponding TME_n values (Roberson et al., 2005). The TME_n values calculated using the prediction equation reported by Batal and Dale correspond well with the determined TME_n values and better than the ME_n values calculated using the NRC equation (Figure 5.1). The TME_n prediction equation by Batal and Dale was based on the determined TME_n values. Thus, the TME_n prediction equation by Batal and Dale should be verified with an independent set of DDGS samples before it is widely used (Black, 1995).

In the study by Batal and Dale, the best single predictor of TME_n content in DDGS was oil content ($r^2 = 0.29$). Because the solubles contain over three times as much oil as do the wet grains, the rate of solubles addition during the DDGS manufacturing process is directly related ($r^2 = 0.88$) to the DDGS TME_n content (Noll, Brannon, and Parsons, 2007; Noll, Parsons, and Dozier, 2007). The oil content of corn DDGS has been reported to vary from 2.5% to 16% in DDGS samples (Batal and Dale, 2006; Parsons et al., 2006; University of Minnesota, 2008b), with substantial potential for variation in TME_n content. Two 2007 studies by Noll and co-authors (Noll, Brannon, and Parsons, 2007; Noll, Parsons, and Dozier, 2007) reported a strong inverse correlation (correlation coefficient, r, = –0.98) between the degree of lightness (L* values) of DDGS and the rate of solubles addition, suggesting that darker DDGS have a greater content of TME_n. However, Fastinger, Latshaw, and Mahan (2006) reported a moderate linear relationship ($r^2 = 0.52$) between the degree of lightness and the TME_n content of DDGS (Figure 5.2). The TME_n and L* values reported in the Noll studies were from DDGS obtained from a single ethanol plant in which the solubles addition rate was experimentally varied, whereas the values by Fastinger, Latshaw, and Mahan were from commercial DDGS samples from different ethanol plants. Moreover, the variation among samples within each study appears to be much smaller in the Noll studies, which may have contributed to the dif-



Modified from Batal and Dale, 2006. Predicted TME_n = 2,732.7 + 36.4 × crude fat – 76.3 × crude fiber + 14.5 × crude protein – 26.2 × ash (Batal and Dale, 2006); predicted ME_n = 39.15 × dry matter – 39.15 × ash – 9.72 × crude protein – 63.81 × crude fiber (NRC, 1994); the chemical composition of the 14 individual corn DDGS samples used in the prediction equations was reported by Batal and Dale (2006).

Figure 5.1. Apparent and true nitrogen-corrected metabolizable energy (ME_n) values of corn distillers dried grains with solubles



Data adapted from Fastinger, Latshaw, and Mahan (2006), ●; and Noll, Parsons, and Dozier (2007), ◆. Greater L* values indicate a lighter color, with values of 0 being completely black and 100 being completely white.

Figure 5.2. Relationship between degree of lightness (L* color value) and true nitrogen-corrected metabolizable energy (TME_n) content of corn distillers dried grains with solubles

ferent results. Nevertheless, the different relationships between L* and TME_n values reported in the Noll studies and by Fastinger, Latshaw, and Mahan suggest that color is not a reliable indicator of energy content in DDGS.

In a recent study, Kim et al. (2008) determined the TME_n contents of conventionally processed DDGS, HP-DDG, and corn germ. The TME_n content of HP-DDG and corn germ was 2,694 and 4,137 kcal/kg, respectively. However, the TME_n value for DDGS determined in the same experiment was 3,266 kcal/kg—outside the range of TME_n values reported for DDGS by Batal and Dale and by Fastinger, Latshaw, and Mahan. Nevertheless, the TME_n of DDGS determined by Kim et al. was within the range reported by Noll and co-authors (2007) after adjusting the rate of solubles addition to the DDGS. The research by Kim et al. showed that the HP-DDG contained about 17% less TME_n than the DDGS used in that study, likely because of a combination of less oil and more protein. Dehydrated corn germ, however, contained about 22% more TME_n than the DDGS, again attributable to the differences in oil and protein contents between the two co-products. Using growing broiler chickens, Thacker and Widyaratne (2007) determined the gross and metabolizable energy contents of a single sample of wheat DDGS from fuel-ethanol production to be 4,724 and 2,387 kcal/kg, respectively.

Amino acids

Corn grain contains 7% to 8% protein, and, because the protein in corn grain is not fermented by yeast, the protein content of DDGS is about three times greater, typically around 27% (Table 5.1). However, the protein content of DDGS has been reported to vary between 23% and 32% (Spiehs, Whitney, and Shurson, 2002; Evonik Degussa, 2005; Batal and Dale, 2006; Fastinger, Latshaw, and Mahan, 2006). This wide range is likely because of differences in the protein content of the corn grain used to produce DDGS and because of differences in residual starch content (diluting the concentrations of protein and other nutrients) caused by differences in fermentation efficiency. Although some DDGS suppliers go to great lengths to minimize variation in nutrient contents (Stein et al., 2006), the amino acid content in DDGS in general can vary substantially. For instance, the content of the first-limiting amino acid for poultry, methionine, has been reported to range from 0.42% to 0.65% (Spiehs, Whitney, and Shurson, 2002; Evonik Degussa, 2005; Fastinger, Latshaw, and Mahan, 2006). Nevertheless, the amino acid content of DDGS is among the main reasons for including this co-product in poultry diets.

The true digestibility of amino acids in DDGS has been reported to vary substantially among ethanol plants (Batal and Dale, 2006; Fastinger, Latshaw, and Mahan, 2006) and it could potentially vary from batch to batch within the same ethanol plant. The main culprit for the variation is the drying process (Fontaine et al., 2007). Different drying techniques (e.g., rotary kiln drying, ring drying), drying temperatures, and drying times can cause inconsistent drying (e.g., "hot spots") or overdrying. Precooking the corn grain to remove unwanted microbial contamination may also be responsible for some of the heat damage. These processes are also the reasons why the amino acid digestibility is lower in DDGS than in corn grain (Table 5.2). In particular, the digestibility of lysine varies substantially because of its susceptibility to heat damage during the drying process (Stein et al., 2006; Fontaine et al., 2007). The epsilon amino group on lysine reacts with reducing sugars in a Maillard reaction. Because poultry do not possess the enzymes to break the bond between lysine and the sugar residue, the Maillard-reaction product either is not absorbed (and therefore excreted into the feces) or is absorbed and—because it is not available for protein synthesis—excreted through the urine. Batal and Dale (2006) measured the true digestibility of lysine in eight DDGS samples using the cecectomized rooster assay; lysine digestibilities ranged from 46% to 78%, with a mean digestibility of 70%. It is noteworthy that the analyzed content of total lysine also varied considerably, from 0.39% total lysine in the DDGS with the lowest digestibility to 0.86% total lysine in the DDGS with the highest digestibility. The low total lysine content in DDGS samples with low lysine digestibility is likely due to partial heat destruction of lysine (Cromwell, Herkelman, and Stahly, 1993; Fontaine et al., 2007; Martinez-Amezcua et al., 2007). While the digestibility varied for all amino acids, the variation in lysine digestibility among DDGS samples was the greatest, suggesting varying degrees of heat damage through differences in drying temperatures and time among ethanol plants. The true amino acid digestibility also varied among the five different DDGS samples tested in a study by Fastinger, Latshaw, and Mahan (2006). The true lysine digestibility varied from 65% to 82%, appearing to be correlated with total lysine content in the DDGS. As before, the lysine digestibility was the most variable, although

Table 5.2. True (or standardized) amino acid digestibilities of corn grain and corn co-products from fuel-ethanol production

Amino acid	Corn Grain[a]	Corn DDGS[b]	Corn HP-DDG[c]	Corn Germ[c]
	%			
Arginine	89	85	91	97
Histidine	94	85	86	86
Isoleucine	88	82	86	91
Leucine	93	89	94	93
Lysine	81	69	73	91
Methionine	91	87	90	91
Cystine	85	77	92	97
Phenylalanine	91	88	91	92
Threonine	84	75	83	90
Tryptophan	–	84	90	–
Valine	88	81	87	91

[a] Data from NRC (1994).
[b] Data from Waldroup et al. (2007).
[c] Data from Kim et al. (2008).

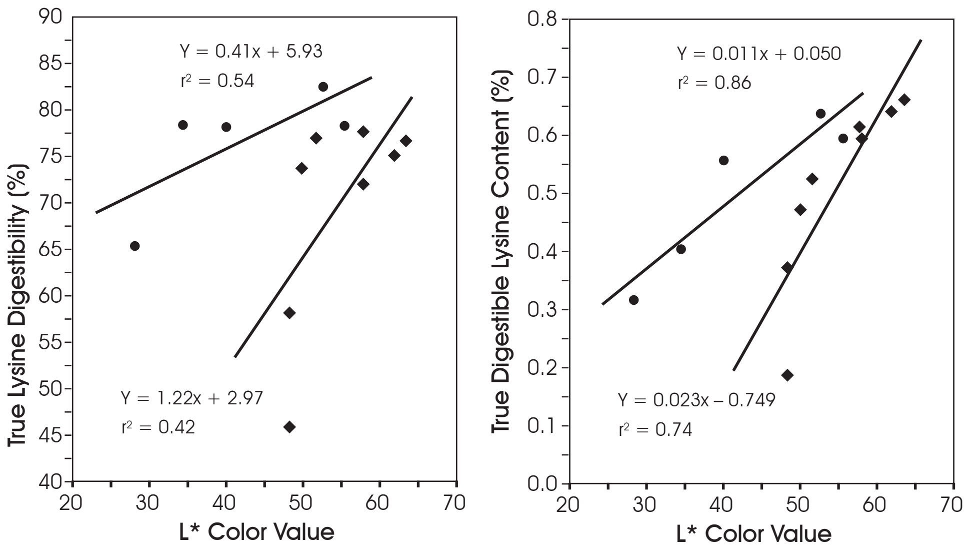
the true cystine digestibility varied substantially as well, also observed by Batal and Dale (2006). Based on a review of the literature, Waldroup et al. (2007) reported weighted averages of amino acid digestibilities for DDGS (Table 5.2); amino acid digestibility values for DDGS are also compiled and reported by Evonik Degussa (2005) and Ajinomoto (2006). The DDGS digestibility values reported by the NRC (1994) are mainly from experiments with DDGS originating from beverage-alcohol production and probably should not be used for DDGS from fuel-ethanol production because of differences in the processes, most notably drying.

Digestibility is an estimate of bioavailability, the latter defined as the portion of amino acids in a feed ingredient that can be used for protein synthesis after consumption. Bioavailability is measured by the slope-ratio method in which the relative bioavailability of a single amino acid in one feed ingredient is compared to that in another feed ingredient (Batterham, Murison, and Lewis, 1979). Estimates of lysine bioavailability in DDGS compared with that of crystalline L-lysine·HCl—which is considered 100% bioavailable (Izquierdo, Parsons, and Baker, 1988)—have been measured by Lumpkins and Batal (2005) using body weight gain of broiler chicks as the response criterion. The relative bioavailability of true digestible lysine in

DDGS was 80% in one experiment and 100% in another experiment. The authors argued that the relative bioavailability of true digestible lysine in DDGS should be 80% of that of L-lysine·HCl. Given the determined true lysine digestibility of 75% in DDGS (Lumpkins and Batal, 2005), it follows that the bioavailable lysine content in the DDGS sample was 60% of the total lysine content. Fontaine et al. (2007) measured the contents of reactive lysine, an estimate of the bioavailable lysine content, in 80 DDGS samples and suggested that 10% to 40% of the lysine in DDGS is heat damaged, and that some overheated batches of DDGS lost up to 59% of their lysine, agreeing with the low bioavailable lysine content determined by Lumpkins and Batal.

The degree of drying (i.e., a combination of the drying temperature and heat-exposure time) affect the amino acid digestibility in DDGS because of Maillard reactions. These reactions between amino acids and sugars generate a characteristic dark color, which can be used as a rough guide for the extent of heat damage to amino acids and ensuing lowered amino acid digestibility (Cromwell, Herkelman, and Stahly, 1993; Batal and Dale, 2006; Fastinger, Latshaw, and Mahan, 2006). In general, samples of DDGS with a lighter and more yellow color (i.e., with greater L* and b* values, respectively) tend to have greater amino acid digestibility values and greater contents of true digestible lysine (Figure 5.3). The rate of addition of solubles to DDGS affects the product's color—a greater addition rate was associated with a darker, less yellow color (i.e., lower L* and b* values), which tended to correlate with true amino acid digestibility, in part because the greater addition rate of solubles warranted greater drying temperatures (Noll, Brannon, and Parsons, 2007; Noll, Parsons, and Dozier, 2007). However, contrary to their expectations, Martinez-Amezcua et al. (2007) did not detect a relationship between the rate of addition of solubles and the true digestibility of amino acids in DDGS. While dietary addition of phytase to DDGS-containing diets improves phosphorus bioavailability, there are minimal, if any, improvements in amino acid digestibility due to phytase addition (Martinez-Amezcua, Parsons, and Baker, 2006).

The amino acid digestibilities of the two co-products from corn fractionation—corn germ and HP-DDG—were reported by Kim et al. (2008), showing that the true amino acid digestibility of corn germ was generally similar to that of HP-DDG, although the true digestibility of some essential



Data adapted from Batal and Dale (2006), ●; and Fastinger, Latshaw, and Mahan (2006), ◆. Greater L* values indicate a lighter color with values of 0 being completely black and 100 being completely white.

Figure 5.3. Relationship between the degree of lightness (L* color value) and lysine digestibility in corn distillers dried grains with solubles

amino acids (i.e., arginine, isoleucine, lysine, and threonine) was greater in corn germ. The true amino acid digestibility of HP-DDG was generally greater than that of unfractionated, conventionally produced DDGS, but, specifically, the true lysine digestibility was not different between the two products. Martinez-Amezcua et al. (2007) produced four different types of corn DDGS co-products, containing from 24% to 41% protein, through corn-grain fractionation and compared their amino acid digestibilities to that of unfractionated, conventionally produced DDGS. The true amino acid digestibilities were not different among the co-products, except for lysine. The true lysine digestibility of unfractionated, conventionally produced DDGS was 66%, lower than three of the four fractionation co-products (with true lysine digestibilities ranging from 77% to 83%). The true lysine digestibility of one fractionation co-product, "dry de-germ de-fiber," was similar to that of unfractionated, conventionally produced DDGS. Thus, the fractionation process can greatly influence the amino acid composition and bioavailability, and care should be taken to use nutrient values and digestibility values obtained using the specific fractionation co-product.

Phosphorus

Corn grain contains about 0.3% phosphorus, but most is contained in phytate and therefore cannot be used by poultry because the birds lack the enzyme phytase to free the phytate phosphorus. In contrast, DDGS contain about 0.7% to 0.8% phosphorus (Table 5.1), most of which is bioavailable. As with other nutrients, the phosphorus content in DDGS varies, with reports ranging widely, from 0.59% to 0.95% (Spiehs, Whitney, and Shurson, 2002; Batal and Dale, 2003; Martinez Amezcua, Parsons, and Noll, 2004; Stein et al., 2006). The large range in phosphorus content stems in part from variation in phosphorus content in corn grain and starch residue in the DDGS, but the rate of addition of solubles to the wet grains prior to drying affects the phosphorus content as well, because the solubles contain more than three times as much phosphorus as do the wet grains (Martinez-Amezcua et al., 2007; Noll, Brannon, and Parsons, 2007; Noll, Parsons, and Dozier, 2007). As with amino acid digestibility, the total phosphorus content of DDGS can be predicted to some extent by looking at the color. The two 2007 Noll studies showed that a greater solubles addition rate to DDGS was associated with a darker color (lower L* color values) and a greater phosphorus content ($r^2 = 0.96$ and 0.98, respectively).

While the phosphorus in corn grain is only about 30% bioavailable (Lumpkins and Batal, 2005), the bioavailability of phosphorus in DDGS is much greater, likely because of heat destruction of phytate during drying (Martinez Amezcua, Parsons, and Noll, 2004; Martinez Amezcua and Parsons, 2007). Martinez Amezcua, Parsons, and Noll (2004) investigated the phosphorus bioavailability relative to that of phosphorus in dipotassium hydrogen phosphoric acid (K_2HPO_4), considered 100% bioavailable, in DDGS samples collected from commercial feed mills, and they determined the two "good quality" samples to have a relative bioavailability of 69% and 75%. Lumpkins and Batal (2005) conducted two experiments comparing the phosphorus bioavailability in DDGS with that of K_2HPO_4. In the first experiment, the phosphorus bioavailability of DDGS was 68%, whereas it was 54% in the second experiment. It is unclear if both experiments used the same sample. Martinez Amezcua, Parsons, and Noll (2004) determined differences in phosphorus bioavailability, ranging from 75% to 102%, among DDGS samples with varying degrees of lysine digestibility. The phosphorus bioavailability appeared to be inversely correlated with lysine digestibility, and the researchers suggested that the degree of heat damage (which reduces lysine digestibility) increases phosphorus bioavailability. This hypothesis was further examined in a subsequent study in which heat damage of DDGS was controlled by autoclaving or oven drying at different temperatures and lengths (Martinez Amezcua and Parsons, 2007). Increased heating of the DDGS increased phosphorus bioavailability from 69% in the control DDGS to as much as 91% in the DDGS sample that was oven-dried at 55°C for three days and then oven-dried at 121°C for sixty minutes. As expected, the lysine digestibility decreased with increasing heat treatment. Based on a review of the literature, Waldroup et al. (2007) suggested a phosphorus bioavailability of 62% (reflected in Table 5.1), set somewhat low to protect against a potential phosphorus deficiency if DDGS provides a substantial amount of dietary phosphorus. The inclusion of citric acid in DDGS-containing diets improved phosphorus bioavailability in a study by Martinez-Amezcua, Parsons, and Baker (2006), as did the addition of a commercially available phytase enzyme. However, the authors noted that the efficacy of the phytase enzyme in improving phosphorus bioavailability depends on the phytate-phosphorus content of the DDGS, which is likely to be affected by processing (heat treatment).

The phosphorus content of co-products from corn fractionated prior to fermentation depends critically on the fractionation method used (Martinez-Amezcua et al., 2007; Kim et al., 2008) and, presumably, so does the bioavailability. The phosphorus content of HP-DDG is lower than that of DDGS, whereas that of corn germ is greater (Table 5.1). However, the relative phosphorus bioavailability of HP-DDG does not appear to be different from that of DDGS, but the bioavailability of phosphorus in dehydrated corn germ is only 25% relative to the bioavailability of phosphorus in K_2HPO_4 (Kim et al., 2008).

Other Minerals

The contents of calcium, potassium, sulfur, and sodium in corn grain are fairly low (Table 5.1). As would be expected, the calcium and potassium contents in DDGS are about three times greater than those in corn grain, but the contents of sulfur and sodium are appreciably greater than what could be expected from the inherent mineral content in corn grain (Table 5.1). The sources of the "extra" sulfur in DDGS include the sulfur in yeast, well water, and sulfuric acid (H_2SO_4) added during the ethanol-production process. Sulfuric acid is added at several stages in the process to adjust the pH to different optimum levels of the carbohydrases and the yeast. Depending on well-water quality and the need for pH adjustments, the sulfur content of DDGS can vary substantially, from 0.3% to well over 1% (Spiehs, Whitney, and Shurson, 2002; Batal and Dale, 2003; University of Minnesota, 2008b). A sulfur level of 0.4% of the complete diet can be toxic to cattle (NRC, 1980), causing polioencephalomalacia; therefore, the sulfur content in DDG or DDGS may limit the inclusion rate of these feed ingredients in cattle feed. In contrast, broiler chickens can tolerate dietary sulfur levels of up to about 0.5%, and laying hens can tolerate even greater levels (Leeson and Summers, 2005), so there do not appear to be any issues with feeding high-sulfur DDGS to poultry. However, sulfur may interfere with calcium and trace mineral absorption in the small intestines and thus bone and eggshell strength (Leeson and Summers, 2001, 2005).

As with sulfur, the content of sodium in DDGS is greater than expected and variable, ranging from about 0.09% to 0.52% (Spiehs, Whitney, and Shurson, 2002; Batal and Dale, 2003; University of Minnesota, 2008b). The sources of the greater-than-expected sodium in DDGS are unknown (Batal and Dale, 2003) but may stem at least in part from differences in water quality at the ethanol plants. While poultry can tolerate high levels of sodium in the diet (Klasing and Austic, 2003), these levels should be monitored and adjusted (e.g., through changes in the salt inclusion rate) when large amounts of high-sodium DDGS are fed to poultry. High dietary sodium levels cause increased water consumption, which may increase the incidences of wet litter and dirty eggs (Leeson et al., 1995; Klasing and Austic, 2003).

Carotenoid Pigments

Corn grain contains carotenoid pigments of which the xanthophylls—zeaxanthin and lutein—are of special interest. When consumed by poultry, xanthophylls are absorbed and deposited in the skin, adipose tissue, and egg yolks, changing their color to the more desirable yellow or red (Ouart et al., 1988; Leeson and Caston, 2004). Consumption of lutein-enriched yolks can help prevent macular degeneration, an age-related chronic eye disease (Leeson and Caston, 2004). Corn grain contains about 20 ppm of xanthophylls (NRC, 1994; Leeson and Summers, 2005), and it is expected the content is concentrated three times in DDGS through removal of starch in the fermentation process. However, the actual xanthophyll content may be lower because of heat destruction during drying. Roberson et al. (2005) analyzed two DDGS samples and observed 30 ppm of xanthophylls in one of the samples, but only 3 ppm in another dark-colored sample considered heat damaged.

Feeding Distillers Dried Grains with Solubles to Poultry

Egg Production (Laying Hens)

Lumpkins, Batal, and Dale (2005) fed diets containing either 0% or 15% corn DDGS to white leghorn-type laying hens from twenty-two weeks of age (corresponding to about four weeks before peak egg production) to forty-three weeks of age. The DDGS inclusion did not affect egg production, egg weight, feed consumption, or feed utilization. Some of the hens in the experiment were also fed a low-density diet in which energy, amino acids, and the nutrient-to-energy ratios were lowered to increase the likelihood that issues with feeding 15% DDGS, if any, could be detected. Compared to the control diet, the low-density 15% DDGS diet resulted in slightly lower egg production and poorer feed utilization. The diets were formulated on a total-amino-acid basis with equal contents of lysine and methionine, suggesting that the 15% DDGS diets were deficient in one or more amino acids due to the lower digestibility of amino acids in DDGS as discussed previously. Roberson et al. (2005) fed DDGS to laying hens at 0%, 5%, 10%, and 15% of the diet. The diets were fed to white leghorn-type hens from forty-eight weeks of age over a period of eight weeks, during which there were inconsistent effects of DDGS on egg production, with a decrease during two of the experiment's eight weeks. Egg weight was not affected, but egg mass (defined as percent egg production × grams of egg weight) decreased in the same weeks that egg production decreased. In Experiment 2—conducted with the same hens from fifty-eight to sixty-seven weeks of age and using a different, darker-colored DDGS sample—egg production and egg mass were not affected, although egg weights decreased linearly during one of the weeks. Neither feed consumption nor feed utilization was affected in either experiment. Roberson et al. concluded that DDGS could be fed to laying hens at levels as high as 15%, whereas Lumpkins, Batal, and Dale recommended a DDGS inclusion level of no more than 10% to 12%. However, the experimental diets in both experiments were formulated using total amino acids, not digestible amino acids, the importance of which was discussed previously. Roberts et al. (2007b) fed diets containing 0% or 10% DDGS to white leghorn-type laying hens from twenty-three to fifty-eight weeks of age and observed no effects on any egg production or egg quality parameters. The diets used in this study were formulated on a digestible-amino-acid basis and to contain similar amounts of apparent ME_n.

Since the published reports by Lumpkins, Batal, and Dale (2005) and Roberson et al. (2005), the laying hen industry in the U.S. Midwest has routinely used diets containing between 5% and 20% DDGS (averaging about 9%), but these inclusion rates have mainly been limited by economics, as the commercial diets are formulated on a least-cost basis in which the relative prices of all ingredients are considered. Feed prices and availability change daily, so the 15% to 20% maximum DDGS inclusion rate does not necessarily reflect an inclusion rate that limits egg production or egg quality. Ignoring the cost of the feed ingredients, Pineda et al. (2008) conducted an experiment to investigate whether egg production and egg quality would be affected by very high inclusion levels of DDGS. In their experiment, graded levels between 0% and 69% DDGS were fed to white leghorn-type laying hens fifty-three weeks of age for eight weeks after a four-week transition period, during which the dietary DDGS contents were gradually changed in steps of about 12 percentage points per week. Egg production decreased linearly during the eight-week experimental period, countered by an increase in egg weight. As a result, egg mass was unaffected by the dietary DDGS inclusion. Feed consumption increased with increasing dietary DDGS content, but feed utilization was unaffected. Egg quality—measured as Haugh units, egg composition, and specific gravity—was not affected by the DDGS inclusion. The experiment by Pineda et al. demonstrated that laying hens can be fed diets with high amounts of DDGS with no adverse effects on egg production and egg quality as long as the energy and nutrient contents of all feed ingredients (including DDGS) are considered and the diets are formulated on a digestible-amino-acid basis. The diets used by Pineda et al. may not have been practical in that they contained high levels of (expensive) supplemental vegetable oil to compensate for the relatively low energy content in DDGS. As a result, the flowability of the DDGS-containing diets was lower than would probably be acceptable on a commercial farm with automatic feeders. More practical inclusion levels were used in an experiment reported by Scheideler, Masa'dah, and Roberson (2008), in which white leghorn-type hens twenty-four weeks of age were fed diets containing graded levels of DDGS of between 0% and 25% for twenty-two weeks. Egg production, feed consumption, and body weight gain were not affected by the dietary DDGS inclusion. Egg weights, however, were lower when the diets contained 20% and 25% DDGS, which the authors attributed to a dietary amino acid deficiency.

Haugh units, a measure of egg interior quality, are not affected by dietary DDGS inclusion and neither is the shell quality, as indicated by the shell breaking-strength or specific gravity of the eggs (Lumpkins, Batal, and Dale, 2005; Roberson et al., 2005; Pineda et al., 2008). That said, consumption of sulfur from sulfur-rich DDGS may interfere with absorption of dietary calcium from the small intestines (Leeson and Summers, 2001, 2005), thereby reducing eggshell quality. Yolk color, however, is affected by the inclusion of the xanthophyll-rich DDGS, such that L* and a* color scores (indicating darker and redder yolks, respectively) increase with increasing dietary DDGS content (Roberson et al., 2005; Roberts et al., 2007b; Pineda et al., 2008).

Effects of feeding corn DDGS to pullets have yet to be published. However, in the laying-hen industry in the U.S. Midwest, DDGS is incorporated into pullet diets at the same levels as routinely fed to laying hens (i.e., up to about 15%, depending on availability and relative price). Because body-weight-for-age of pullets is an important criterion for developing high-quality laying hens (Leeson and Summers, 2005), research with broiler chickens can be used as a rough guide for using DDGS in pullet diets. Similarly, the effects of feeding DDGS to breeding broiler or turkey hens have not been published. However, research with laying hens can be used as a rough guide for using DDGS in broiler and turkey breeder diets.

Meat Production (Broiler Chickens and Turkeys)

Lumpkins, Batal, and Dale (2004) fed 0% or 15% DDGS to Cobb-500 straight-run broiler chickens from one to eighteen days of age and found no adverse effects on body-weight gain or feed utilization. However, when the diets were formulated to contain lower energy and protein contents to increase the likelihood of detecting differences in growth performance due to DDGS, feed utilization was adversely affected in broilers fed the 15% DDGS diet. This effect was evident during the first two weeks of age, but there were no effects of DDGS at eighteen days of age. In a subsequent experiment, Lumpkins, Batal, and Dale fed 0%, 6%, 12%, and 18% DDGS to one-day-old Cobb-500 chicks until an age of forty-two days. In this experiment, body-weight gain and feed utilization were unaffected by feeding up to 12% DDGS, but gain and feed utilization were lowered when broilers were fed the 18% DDGS diet, which the authors attributed to an amino acid deficiency (likely lysine) in the starter diet. Based on their study, Lumpkins, Batal, and Dale recommended that no more than 12% DDGS be included in the starter diets but that grower and finisher diets could contain 12% to 15% DDGS. However, all diets in the experiments by Lumpkins, Batal, and Dale were balanced on a total-amino-acid basis. Given the relatively low amino acid digestibilities of DDGS, it is possible that the reduced growth performance at high DDGS inclusion levels was caused by an amino acid deficiency (e.g., lysine or arginine).

Wang et al. (2007c) balanced broiler diets on a digestible-amino-acid basis using a standardized nutrient matrix for DDGS (shown in Table 5.1) and dietary digestible amino acid levels based on industry averages. In the study, graded levels of DDGS between 0% and 25% were fed to male Cobb-500 chickens from one to forty-nine days of age with no treatment effects on body-weight gain. However, cumulative feed consumption from zero to thirty-five and from zero to forty-nine days of age increased compared with the control diet when the diet contained 25% DDGS. As a result, the cumulative feed utilization was adversely affected during the same age periods. A careful examination of the analyzed (total) amino acid concentrations in the diets suggests that the 25% DDGS diets may have been marginally limiting in arginine with observed arginine-to-lysine ratios between 102% and 104%, depending on the specific diet. The ideal arginine-to-lysine ratio (albeit expressed on a digestible basis) is 105% to 111% (Baker and Han, 1994; Mack et al., 1999; Baker, 2003), somewhat greater than the arginine-to-lysine ratios calculated from data presented by Wang et al. (2007c).

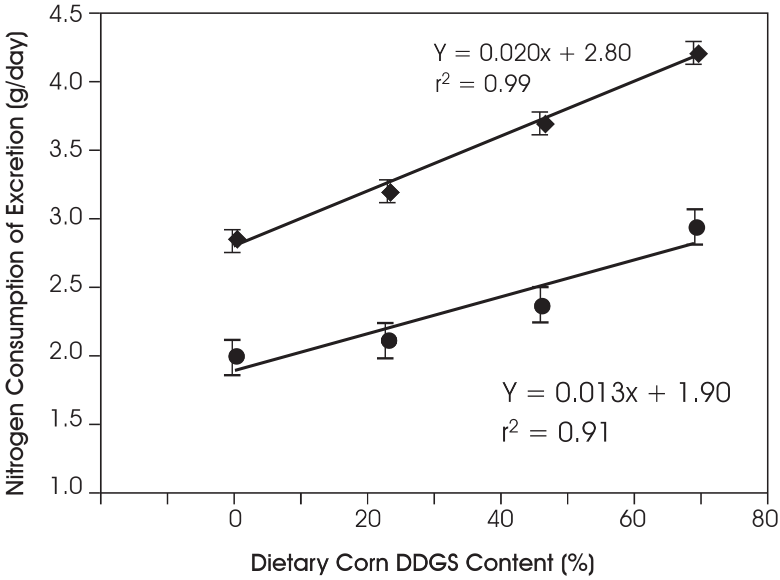
Young broiler chicks are sensitive to feed ingredient quality because their digestive systems are not fully developed until about fourteen days of age (Batal and Parsons, 2002a,b). Because of the high fiber content and low amino acid digestibility of DDGS, feeding diets containing 25% to 30% DDGS during the two first weeks after hatch is not recommended. Indeed, Wang et al. (2007b) observed a trend toward decreased body weight during the initial two weeks after hatch in broilers fed diets containing 30% DDGS compared to 0% or 15% DDGS, and the broilers' body weights continued to lag behind those of control-fed broilers throughout the forty-two-day study. Feed utilization was significantly lower throughout the study for broilers fed the 30% DDGS diet compared to broilers fed 0% or 15% DDGS. When DDGS was omitted from starter diets (one to fourteen days of age), but introduced in grower diets (fourteen to thirty-five days of age) at 15% and subsequently kept constant or further increased in the finisher diets fed for the last seven days before slaughter (i.e., 0%-15%-15% or 0%-15%-30% DDGS), body weight, feed consumption, and feed utilization at forty-two days of age were similar to those of broilers fed no DDGS. However, when 30% DDGS content was included in the diets, either from one day of age or introduced in grower or finisher diets, growth performance was depressed. Similarly, in a third study, Wang et al. (2007a) fed diets containing 0%, 15%, or 30% DDGS to Cobb-500 broiler chicks throughout the growing period from one to forty-two days of age and observed no effect of feeding 15% DDGS, but depressed growth performance was observed when the diet containing 30% DDGS was fed. In both studies, an arginine deficiency may be the culprit, as the arginine-to-lysine ratios, calculated from the reported dietary total amino acid values, were between 82% and 93% in the diets containing 30% DDGS (Wang et al., 2007a,b). Poor pellet quality will result in poorer growth performance and interact with dietary protein quality such that diets with poor pellet quality must contain a greater amount of balanced (or ideal) protein to achieve the same growth performance as diets with good pellet quality (Greenwood, Clark, and Beyer, 2004; Lemme et al., 2006). The diets in the studies by Wang et al. (2007a,b) were pelleted, and pellet quality decreased with increasing DDGS content. Therefore, it is possible that the poorer performance of broilers fed the 30% DDGS diet was, at least in part, due to pellet quality.

In some (Whitney et al., 2006; Linneen et al., 2008)—but not all (Widmer et al., 2008)—studies with pigs, dietary inclusion of DDGS decreased the dressing percentage, presumably because of the empty entrails and water retention within the digesta attributed to an increased dietary fiber content (Linneen et al., 2008). Although similar effects of DDGS on dressing percentage would be expected in poultry for the same reasons as in pigs, dressing percentage was not affected in broilers fed diets containing up to 30% DDGS (Lumpkins, Batal, and Dale, 2004; Wang et al., 2007a,b). In a study by Wang et al. (2007c), however, dressing percentage appeared to decrease linearly with increased DDGS content. Compared to the control diet, the dressing percentage was lower when broilers were fed diets containing 15% and 25% DDGS, but not in diets containing 5%, 10%, and 20% DDGS. Despite decreased growth performance in broilers fed 18% DDGS (Lumpkins, Batal, and Dale, 2004), breast-meat yield and other cuts were unaffected by the dietary treatments whether they were measured on a gram-per-bird basis or a percentage-of-carcass-weight basis. Similarly, Wang et al. (2007a,b) observed no effects on carcass quality when broilers were fed up to 15% DDGS. However, when fed 30% DDGS, broilers had lower breast-meat yield (Wang et al., 2007a,b), likely attributable to an arginine deficiency (Corzo, Moran, and Hoehler, 2003) as previously described.

Roberson (2003) conducted an experiment with turkey hens fed DDGS-containing diets from 56 to 105 days of age, at which time the hens were sent to a commercial processing plant. The diets contained up to 27% DDGS and were formulated on a digestible-amino-acid basis. Body-weight gain decreased linearly with increasing DDGS content, attributed to a deficiency in digestible lysine, likely caused by a lower-than-expected digestibility value. In a second experiment, DDGS was included at up to 10% of the diet with no effects on body-weight gain or feed conversion of the turkeys. Carcass quality was not investigated in the experiment by Roberson, but Noll et al. (2002) reported no adverse effects on breast-meat yield of feeding DDGS to turkey toms as long as needed amino acid levels were met.

Environmental Aspects of Feeding Distillers Dried Grains with Solubles to Poultry

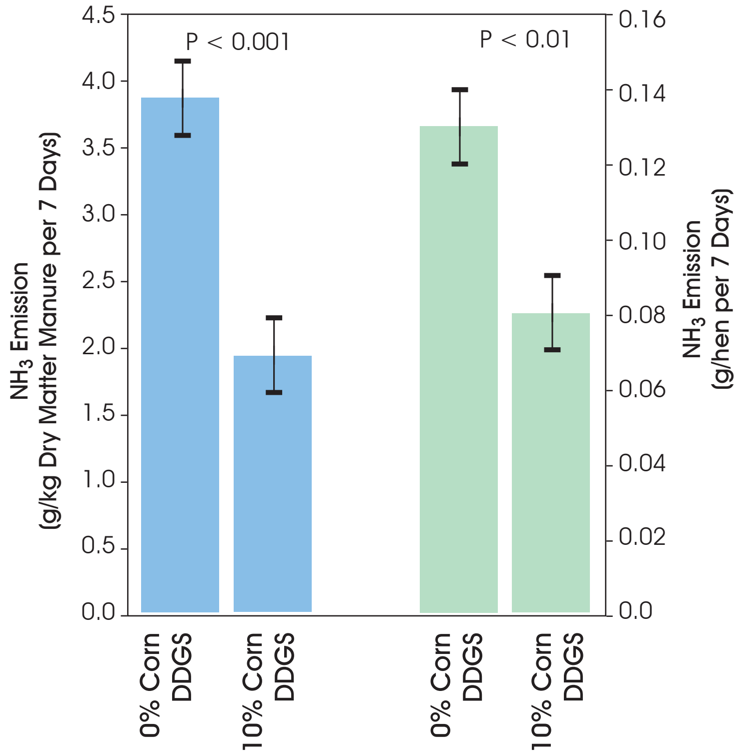
In part because of the relatively low amino acid digestibility in DDGS and in part because of an amino acid profile different from that of soybean meal, protein levels in DDGS-containing diets are expected to be greater than if the diet is formulated with corn grain and soybean meal only. Depending on the magnitude of the dietary DDGS inclusion rate, both nitrogen consumption and excretion from the birds are expected to increase (Roberts et al., 2007b; Pineda et al., 2008) (Figure 5.4). Although increased ammonia (NH_3) emission from the manure is associated with increased nitrogen excretion (Summers, 1993; Kerr and Easter, 1995; Keshavarz and Austic, 2004), dietary DDGS appear



Data adapted from Pineda et al. (2008). Dots represent means ± pooled SEM of six observations.

Figure 5.4. Nitrogen consumption (◆) and excretion (●) by laying hens fed diets containing up to 69% corn distillers dried grains with solubles

to have an attenuating effect on ammonia emissions (Roberts et al., 2007a) (Figure 5.5). Fiber is not digested by the birds, and some of it is instead fermented by microbes in the large intestines, producing short-chain fatty acids, which in turn lower the manure pH. The lowered pH results in a shift in the NH_3 equilibrium toward the less-volatile ammonium ion ($NH_3 + H^+ \leftrightarrow NH_4^+$). Therefore, poultry fed DDGS may excrete more nitrogen, but because of the resultant lower manure pH, the nitrogen does not evaporate off. This effect of dietary fiber on manure acidification and NH_3 emission was first demonstrated in pigs by Canh et al. (1998a,b) and later in laying hens by Roberts et al. (2007a) using DDGS-containing diets. Hence, at first glance, it appears that an increase in dietary crude protein content of DDGS-containing diets may have adverse effects on air quality and the environment because of increased nitrogen excretion. However, the nitrogen appears to remain in the manure, which, when applied correctly on fields, does not adversely affect the environment and may increase the fertilizer and therefore the economic value of the manure.



Data adapted from Roberts et al. (2007a). Bars represent means ± pooled SEM of 32 observations.

Figure 5.5. Ammonia emissions from laying hens fed diets containing 0% or 10% corn distillers dried grains with solubles

Formulating Diets with Distillers Dried Grains with Solubles for Poultry

Traditionally, corn grain and soybean meal have supplied the majority of amino acids in midwestern poultry diets. Corn protein is relatively high in methionine and low in lysine, whereas the opposite is true in soybean protein, illustrated by the differences in their methionine-to-lysine ratios (Table 5.3). Hence, corn grain and soybean meal complement each other very well in meeting the amino acid needs of poultry. The amino acid ratios in corn grain and DDGS are similar (Table 5.3). Therefore, the amino acids in corn grain and DDGS do not complement each other. This discrepancy in amino acid profile ("protein quality") between distillers co-products and other protein supplements has been recognized for a long time (Morrison, 1954) and so, despite the relatively high protein

Table 5.3. Amino acid profiles of corn grain, corn co-products from fuel-ethanol production, and soybean meal (lysine = 100%)

Amino acid	Corn Grain[a]	Corn DDGS[b]	Corn HP-DDG[c]	Corn Germ[c]	Soybean Meal[a]
	%				
Lysine	100	100	100	100	100
Arginine	146	149	126	143	118
Histidine	88	93	96	53	43
Isoleucine	112	132	121	56	72
Leucine	385	411	454	132	126
Methionine	69	68	83	32	23
Cystine	69	74	118	46	24
Methionine + cystine	138	142	201	77	47
Phenylalanine	146	179	192	76	79
Threonine	112	132	137	72	63
Tryptophan	23	29	29	24	25
Valine	154	178	172	85	75

[a]Calculated from NRC (1994).
[b]Calculated from Waldroup et al. (2007).
[c]Calculated from Poet Nutrition (2008).

content, DDGS cannot be viewed as a replacement for soybean meal or other protein supplements in poultry diets.

It is evident from the studies reported in this chapter that DDGS from fuel-ethanol production can make up a substantial portion of diets for broiler chickens, turkeys, and laying hens, provided the diet supplies all the nutrients in the right amounts and proportions. When DDGS-containing diets failed to meet egg production, growth performance, or carcass quality expectations, it could almost always be attributed to an amino acid deficiency, illustrating the important differences in amino acid profiles between DDGS and soybean meal and the differences in amino acid digestibility. Special care should be taken by nutritionists to monitor the dietary contents of all amino acids, for instance, through the ideal amino acid ratio. Ideal amino acid ratios have been published for broilers (Baker and Han, 1994; Mack et al., 1999; Baker, 2003; Rostagno, 2005), turkeys (Firman and Boling, 1998), and laying hens (Coon and Zhang, 1999; Rostagno, 2005; Bregendahl et al., 2008) or they can be calculated from tables of nutrient requirements and recommendations (e.g., NRC, 1994; Centraal Veevoederbureau, 1996; Leeson and Summers, 2005).

Furthermore, because of the relatively low amino acid digestibilities in DDGS, it is especially important to formulate poultry diets on a true digestible-amino-acid basis when uncluding DDGS in diets. If the DDGS-containing diet is formulated on a total-amino-acid basis, only a relatively small amount (5% to 10%) can be included in poultry diets without affecting production. To illustrate the importance of formulating diets on a true digestible basis, three different sets of laying hen diets were formulated (Table 5.4) using either a crude protein minimum of 17% (with a total methionine+cystine minimum), on a total-amino-acid basis (with no crude protein minimum), or on a true digestible-amino-acid basis (with no crude protein minimum). Diets were also formulated with or without 15% DDGS to illustrate the effects of the low amino acid digestibility in DDGS. The dietary lysine content was set to 0.80% total lysine in the diet formulated on total amino acids and to 0.72% true digestible lysine in the diet formulated on a true digestible-amino-acid basis; the requirements for all other amino acids were determined using the ideal amino acid profile reported by Bregendahl et al. (2008). The nutrient contents listed by the NRC (1994) were used for all ingredients, except for DDGS, which used nutrient contents reported by Poet Nutrition (2007) and an available phosphorus content conservatively set at 54% of total phosphorus (Lumpkins and Batal, 2005). The true amino acid digestibility values reported by Ajinomoto (2006) were used for all ingredients. Although the diets were not formulated to be "least-cost diets," the diet costs were calculated using feed ingredient prices from the December 10, 2007, edition of *Feedstuffs* magazine (Minneapolis prices). If it is accepted that the best estimate of the hens' amino acid needs are the true digestible amino acid requirement, then is it evident from Table 5.4 that a diet formulated to contain 17% crude protein from corn, soybean meal, and meat and bone meal will be marginally deficient in methionine+cystine and threonine when amino acid digestibilities are considered. These deficiencies were exacerbated when DDGS was included in the diet. Formulating on total amino acids also resulted in marginal deficiencies when digestibility was considered, yet there may have been some benefits of a concomitant lowered diet cost (although this benefit is likely to be offset by a reduction in performance due to the amino acid deficiencies). The only scenario in which there were no deficiencies was when the diets were formulated on true digestible amino acids, demonstrating the benefits of formulating diets this way. Similar conclusions were reached by Pineda et al. (2008) after an experiment in

Table 5.4. Examples of laying hen diets formulated based on crude protein, total amino acids, or true digestible amino acids with or without corn distillers dried grains with solubles (DDGS)

Item	Minimum Recommended Content	Formulated Using Crude Protein Minimum Corn DDGS		Formulated Using Total Aminoa Acids Corn DDGS		Formulated Using True Digestible Amino Acids Corn DDGS	
		0%	15%	0%	15%	0%	15%
Ingredient							
Corn DDGS	–	–	15.00	–	15.00	–	15.00
Corn grain	–	63.25	54.65	64.70	53.87	63.53	52.26
Soybean meal	–	18.27	11.78	17.00	12.50	18.00	14.00
Meat and bone meal	–	5.50	5.10	5.50	5.00	5.50	4.75
Vegetable oil	–	1.86	2.29	1.64	2.40	1.82	2.65
DL-Methionine	–	0.19	0.14	0.21	0.13	0.20	0.14
L-Lysine·HCl	–	–	–	–	0.03	–	0.06
L-Threonine	–	–	–	0.02	0.02	0.02	0.01
Calcium carbonate	–	10.18	10.29	10.18	10.30	10.18	10.38
Sodium chloride	–	0.25	0.25	0.25	0.25	0.25	0.25
Trace mineral premix	–	0.25	0.25	0.25	0.25	0.25	0.25
Vitamin premix	–	0.25	0.25	0.25	0.25	0.25	0.25
Total	–	100.00	100.00	100.00	100.00	100.00	100.00
Calculated chemical composition							
ME_n, kcal/kg	2,850	2,850	2,850	2,850	2,850	2,850	2,850
Crude protein	–	17.00	17.00	16.55	17.27	16.92	17.74
Ether extract	–	4.96	6.46	4.79	6.54	4.93	6.71
Linoleic acid	2.00	2.40	3.27	2.31	3.31	2.38	3.40
Calcium	4.45	4.45	4.45	4.45	4.45	4.45	4.45
Phosphorus, available	0.44	0.44	0.44	0.44	0.44	0.44	0.44

Table 5.4. Continued

Item	Minimum Recommended Content	Formulated Using Crude Protein Minimum Corn DDGS 0%	Formulated Using Crude Protein Minimum Corn DDGS 15%	Formulated Using Total Aminoa Acids Corn DDGS 0%	Formulated Using Total Aminoa Acids Corn DDGS 15%	Formulated Using True Digestible Amino Acids Corn DDGS 0%	Formulated Using True Digestible Amino Acids Corn DDGS 15%
Total amino acids[a]							
Arginine	0.86	1.06	0.98	1.02	1.00	1.05	1.04
Histidine	–	0.43	0.45	0.42	0.45	0.43	0.46
Isoleucine	0.63	0.66	**0.62**	0.63	0.63	0.65	0.65
Lysine	0.80	0.85	**0.76**	0.81	0.80	0.84	0.86
Methionine	0.38	0.46	0.43	0.48	0.42	0.47	0.44
Methionine+cystine	0.75	0.75	0.75	0.75	0.75	0.75	0.77
Threonine	0.62	0.62	**0.61**	0.62	0.64	0.64	0.65
Tryptophan	0.18	0.19	**0.17**	0.18	0.18	0.19	0.19
Valine	0.74	0.79	0.79	0.77	0.80	0.78	0.82
True digestible amino acids[a]							
Arginine	0.77	0.97	0.91	0.93	0.91	0.96	0.95
Histidine	–	0.38	0.38	0.37	0.38	0.38	0.39
Isoleucine	0.57	0.59	**0.56**	0.57	**0.56**	0.59	0.59
Lysine	0.72	0.75	**0.66**	0.72	**0.66**	0.74	0.72
Methionine	0.34	0.44	0.39	0.45	0.39	0.45	0.41
Methionine+cystine	0.68	**0.67**	**0.66**	0.68	**0.66**	0.68	0.68
Threonine	0.55	**0.54**	0.55	**0.54**	0.55	0.55	0.56
Tryptophan	0.16	0.16	**0.15**	**0.15**	**0.15**	0.16	0.16
Valine	0.67	0.70	0.70	0.68	0.70	0.70	0.72
Diet cost, $/907 kg	–	175	165	173	167	175	171

[a]Amino acid values in bold font are below recommended contents.

which no effects on egg production or egg quality were detected between hens fed a control diet or a diet containing 69% DDGS. Correspondingly, Rostagno and Pupa (1995) and Hoehler et al. (2005) demonstrated the superiority of formulating broiler diets on a digestible-amino-acid basis rather than a total-amino-acid basis.

Different cereal grains (e.g., corn, wheat, sorghum, barley, and rye) can be used as a substrate for fuel-ethanol production, and the differences in chemical composition of the cereal grains are reflected in the DDGS. However, taking these differences into account, there do not seem to be major differences among DDGS originating from different grains with regard to diet formulation strategies, nutrient utilization, or growth and performance (Nyachoti et al., 2005; Thacker and Widyaratne, 2007).

Potential Practical Limitations for Use of Distillers Dried Grains with Solubles in Poultry Diets

When economic restraints are removed and only the feed ingredients' content of energy and nutrients and their desired concentrations restrain diet formulation, as much as 70% DDGS can be included in a laying-hen diet (Pineda et al., 2008). However, while there may be no nutritional or production effects of such high dietary DDGS levels, other factors may limit the dietary inclusion rate of DDGS. For instance, the relatively low energy content of DDGS warrants a greater inclusion of supplemental oil or fat, which may increase the diet cost as well as decrease the flowability of the diet, thereby causing problems associated with bridging (Waldroup et al., 1981; Pineda et al., 2008). The bulk density of DDGS averages 570 g/L (35.7 lb/ft^3), although with some variation among samples from different ethanol plants (U.S. Grains Council, 2008). In comparison, the bulk density of ground corn grain is approximately 580 g/L (36.2 lb/ft^3), and that of soybean meal is around 630 g/L (39.4 lb/ft^3) (Jurgens and Bregendahl, 2007), meaning that the density of DDGS-containing diets tends to decrease with increasing DDGS content (Wang et al., 2007a,b,c). The lower bulk density of DDGS-containing diets means that less feed (on a weight basis) can be transported in each truck from the feed mill to the poultry barn and that gut-fill may limit feed consumption by the birds. As a result, the upper practical limit for DDGS inclusion in mash or meal diets is likely somewhere around 20% to 25% of the diet, with greater levels requiring pelleting, flow agents, or antioxidants. Pelleting of DDGS-containing diets is possible, but there may be difficulties if the diet contains more than 5% to 7% DDGS (Behnke, 2007). The pelleting difficulties stem in part from an increase in the dietary oil content (some of which comes from the DDGS) and in part because DDGS lack starch, which otherwise helps bind the pellets together (Behnke, 2007). However, pelleting issues with high DDGS inclusion are manageable, as shown by Wang et al. (2007a,b,c), who conducted broiler feeding trials with pelleted diets containing up to 30% DDGS. Although pellet durability was not specifically tested in these studies, Wang et al. (2007a,b) reported that the pellet quality of the diet containing 15% DDGS was similar to that of the control diet, but the diet containing 30% DDGS pelleted poorly and contained numerous fines despite the addition of a pellet binder.

Almost all commercial poultry diets are formulated on a least-cost basis, and the choice of ingredients and their inclusion levels are usually reevaluated on a weekly basis. Large fluctuations in price and availability of DDGS may therefore result in similarly large fluctuations in the dietary content of DDGS. Potentially, a diet can contain 0% DDGS one week and, say, 20% the next. Such rapid and large shifts in ingredients may cause temporary decreases in the birds' feed consumption and therefore persistent decreases in growth rate and feed utilization due to changes in pellet quality, smell, taste, or physical appearance of the feed. To test if fluctuations in the dietary DDGS content would affect growth performance and carcass quality of broilers, Wang et al. (2007a) conducted an experiment in which broilers were fed diets containing 0%, 15%, or 30% DDGS. The dietary content of DDGS fluctuated on a weekly basis between 0% and 15% or between 0% and 30% DDGS, and growth performance was compared to broilers fed 0%, 15%, or 30% DDGS throughout the six-week experiment. There were no adverse effects of feeding diets containing 15% DDGS, and it did not matter if the DDGS levels fluctuated weekly or were constant, or if the diets contained 0% or 15% DDGS during the first or last week of the experiment. However, broilers fed fluctuating levels of either 0% or 30% DDGS gained less body weight and had lower breast-meat yield than birds fed 0% DDGS if the feed during the last week before slaughter contained 30% DDGS. If the dietary DDGS content fluctuated such that the last week's feed contained 0% DDGS, body-weight gain and breast-meat yield was similar to that of broilers fed 0% DDGS throughout the experiment. Potential reasons for the reduced performance of broilers fed 30% DDGS include an arginine deficiency, perhaps combined with poor pellet quality as discussed previously. Nevertheless, it appears that broiler chickens are able to adapt to large and rapid changes in dietary DDGS content. A similar adaptability to weekly changes in dietary DDGS was observed in laying hens by Pineda et al. (2008), who increased the DDGS contents by about 12 percentage points on a weekly basis starting from 10% DDGS and ending with 69% DDGS with no adverse effects on egg production.

Conclusion

Corn DDGS and other distillers co-products are valuable sources of energy and nutrients in poultry diets. However, in part because of variation in energy and nutrient contents among and within co-products, care should be taken in formulating the diets. Preferably, the co-products should be from a single source to minimize variation, and chemical analyses should be performed to verify the nutrient composition and to estimate nutrient availability. When the diets are formulated on a digestible-amino-acid basis, the co-products can be included at 15% of the diet or higher for broilers, turkeys, and laying hens, although poultry feeders are advised to start at lower inclusion levels in young birds and gradually increase the inclusion level as the birds mature.

References

Ajinomoto. 2006. "True Digestibility of Essential Amino Acids for Poultry," (revision 7, table). http://www.lysine.com/new/Technical%20Reports/Poultry/PoultryDigTableV7.pdf (accessed December 10, 2007).

Association of American Feed Control Officials (AAFCO). 2007. AAFCO Official Publication. Reference manual. Oxford, IN: AAFCO.

Baker, D.H. 2003. "Ideal Amino Acid Patterns for Broiler Chicks." In *Amino Acids in Animal Nutrition*, pp. 223–235. J.F.P. D'Mello, ed. Oxon, UK: CABI Publishing.

Baker, D.H., and Y. Han. 1994. "Ideal Amino Acid Profile for Chicks during the First Three Weeks Posthatching." *Poult. Sci.* 73: 1441–1447.

Batal, A., and N. Dale. 2003. "Mineral Composition of Distillers Dried Grains with Solubles." *J. Appl. Poult. Res.* 12: 400–403.

Batal, A.B., and N.M. Dale. 2006. "True Metabolizable Energy and Amino Acid Digestibility of Distillers Dried Grains with Solubles." *J. Appl. Poult. Res.* 15: 89–93.

Batal, A.B., and C.M. Parsons. 2002a. "Effects of Age on Development of Digestive Organs and Performance of Chicks Fed a Corn–Soybean Meal versus a Crystalline Amino Acid Diet." *Poult. Sci.* 81: 1338–1341.

———. 2002b. "Effects of Age on Nutrient Digestibility in Chicks Fed Different Diets." *Poult. Sci.* 81: 400–407.

Batterham, E.S., R.D. Murison, and C.E. Lewis. 1979. "Availability of Lysine in Protein Concentrates as Determined by the Slope-Ratio Assay with Growing Pigs and Rats and by Chemical Techniques." *Br. J. Nutr.* 41: 383–391.

Behnke, K.C. 2007. "Feed Manufacturing Considerations for Using DDGS in Poultry and Livestock Diets." In *Proceedings of the 5th Mid-Atlantic Nutrition Conference,* pp. 77–81. N.G. Zimmerman, ed. College Park, MD: Maryland Feed Industry Council and Dept. of Animal and Avian Sciences, University of Maryland.

Black, J.L. 1995. "The Testing and Evaluation of Models." In *Modeling Growth in the Pig,* pp. 23–31. EAAP Publication No. 78. P.J. Moughan, M.W.A. Verstegen, and M.I. Visser-Reyneveld, eds. Wageningen: Wageningen Press.

Bregendahl, K., S.A. Roberts, B. Kerr, and D. Hoehler. 2008. "Ideal Ratios of Isoleucine, Methionine, Methionine plus Cystine, Threonine, Tryptophan, and Valine Relative to Lysine for White Leghorn-Type Laying Hens of Twenty-Eight to Thirty-Four Weeks of Age." *Poult. Sci.* 87: 744–758.

Canh, T.T., A.J.A. Aarnink, J.B. Schutte, A. Sutton, D.J. Langhout, and M.W.A. Verstegen. 1998a. "Dietary Protein Affects Nitrogen Excretion and Ammonia Emission from Slurry of Growing–Finishing Pigs." *Livest. Prod. Sci.* 56: 181–191.

Canh, T.T., A.J.A. Aarnink, M.W.A. Verstegen, and J.W. Schrama. 1998b. "Influence of Dietary Factors on the pH and Ammonia Emission of Slurry from Growing–Finishing Pigs." *J. Anim. Sci.* 76: 1123–1130.

Centraal Veevoederbureau. 1996. "Aminozurenbehoefte van Leghennen en Vleeskuikens" [Amino acid requirements for laying hens and broiler chickens]. Documentation Report nr. 18 (in Dutch). Lelystad, The Netherlands.

Coon, C., and B. Zhang. 1999. "Ideal Amino Acid Profile for Layers Examined." *Feedstuffs* 71(14): 13–15, 31.

Corzo, A., E.T. Moran, Jr., and D. Hoehler. 2003. "Arginine Need of Heavy Broiler Males: Applying the Ideal Protein Concept." *Poult. Sci.* 82: 402–407.

Cromwell, G.L., K.L. Herkelman, 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.

Evonik Degussa. 2005. AminoDat 3.0., platinum version. Evonik Degussa, Hanau-Wolfgang, Germany.

Fastinger, N.D., J.D. Latshaw, and D.C. Mahan. 2006. "Amino Acid Availability and True Metabolizable Energy Content of Corn Distillers Dried Grains with Solubles in Adult Cecectomized Roosters." *Poult. Sci.* 85: 1212–1216.

Firman, J.D., and S.D. Boling. 1998. "Ideal Protein in Turkeys." *Poult. Sci.* 77: 105–110.

Fontaine, J., U. Zimmer, P.J. Moughan, and S.M. Rutherfurd. 2007. "Effect of Heat Damage in an Autoclave on the Reactive Lysine Contents of Soy Products and Corn Distillers Dried Grains with Solubles: Use of the Results to Check on Lysine Damage in Common Qualities of these Ingredients." *J. Agric. Food Chem.* 55: 10737–10743.

Greenwood, M.W., P.M. Clark, and R.S. Beyer. 2004. "Effect of Feed Fines Level on Broilers Fed Two Concentrations of Dietary Lysine from 14 to 30 Days of Age." *Int. J. Poult. Sci.* 3: 446–449.

Hoehler, D., A. Lemme, V. Ravindran, W.L. Bryden, and H.S. Rostagno. 2005. "Feed

Formulation in Broiler Chickens Based on Standardized Ileal Amino Acid Digestibility." In *Proceedings of the 3rd Mid-Atlantic Nutrition Conference,* pp. 78–91. N.G. Zimmerman, ed. College Park, MD: Maryland Feed Industry Council and Dept. of Animal and Avian Sciences, University of Maryland.

Izquierdo, O.A., C.M. Parsons, and D.H. Baker. 1988. "Bioavailability of Lysine in l-Lysine HCl." *J. Anim. Sci.* 66: 2590–2597.

Jurgens, M.H., and K. Bregendahl. 2007. *Animal Feeding and Nutrition*, 10th ed. Dubuque, IA: Kendall/Hunt Publishing Company.

Kerr, B.J., and R.A. Easter. 1995. "Effect of Feeding Reduced Protein, Amino Acid-Supplemented Diets on Nitrogen and Energy Balance in Grower Pigs." *J. Anim. Sci.* 73: 3000–3008.

Keshavarz, K., and R. Austic. 2004. "The Use of Low-Protein, Low-Phosphorus, Amino-Acid- and Phytase- Supplemented Diets on Laying Hen Performance and Nitrogen and Phosphorus Excretion." *Poult. Sci.* 83: 75–83.

Kim, E.J., C.M. 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." *Poult. Sci.* 87: 700–705.

Klasing, K.C., and R.E. Austic. 2003. "Nutritional Diseases." In *Diseases of Poultry*, 11th ed., pp. 1027–1053. Y.M. Saif, ed. Ames, IA: Iowa State Press.

Leeson, S., and L. Caston. 2004. "Enrichment of Eggs with Lutein." *Poult. Sci.* 83: 1709–1712.

Leeson, S., G. Diaz, and J.D. Summers. 1995. *Poultry Metabolic Disorders and Mycotoxins.* Guelph, ON: University Books.

Leeson, S., and J.D. Summers. 2005. *Commercial Poultry Production,* 3rd ed. Guelph, ON: University Books.

———. 2001. *Nutrition of the Chicken,* 4th ed. Guelph, ON: University Books.

Lemme, A., P.J. Wijtten, J. van Wichen, A. Petri, and D.J. Langhout. 2006. "Responses of Male Growing Broilers to Increasing Levels of Balanced Protein Offered as Coarse Mash or Pellets of Varying Quality." *Poult. Sci.* 85: 721–730.

Leske, K.L., O. Akavanichan, T.K. Cheng, and C.N. Coon. 1991. "Effect of Ethanol Extract on Nitrogen-Corrected True Metabolizable Energy for Soybean Meal with Broilers and Roosters." *Poult. Sci.* 70: 892–895.

Linneen, S.K., J.M. Derouchey, S.S. Dritz, R.D. Goodband, M.D. Tokach, and J.L. Nelssen. 2008. "Effects of Dried Distiller Grains with Solubles on Growing and Finishing Pig Performance in a Commercial Environment." *J. Anim. Sci.* 86: 1579–1587.

Lumpkins, B.S., and A.B. Batal. 2005. "The Bioavailability of Lysine and Phosphorus in Distillers Dried Grains with Solubles." *Poult. Sci.* 84: 581–586.

Lumpkins, B.S., A. Batal, and N. Dale. 2005. "Use of Distillers Dried Grains plus Solubles in Laying Hen Diets." *J. Appl. Poult. Res.* 14: 25–31.

Lumpkins, B.S., A.B. Batal, and N.M. Dale. 2004. "Evaluation of Distillers Dried Grains with Solubles as a Feed Ingredient for Broilers." *Poult. Sci.* 83: 1891–1896.

Mack, S., D. Bercovici, G. De Groote, B. Leclercq, M. Lippens, M. Pack, J.B. Schutte, and S. van Cauwenberghe. 1999. "Ideal Amino Acid Profile and Dietary Lysine Specification for Broiler Chickens of 20 to 40 Days of Age." *Br. Poult. Sci.* 40: 257–265.

Martinez-Amezcua, C., C.M. Parsons, and D.H. Baker. 2006. "Effect of Microbial Phytase and Citric Acid on Phosphorus Bioavailability, Apparent Metabolizable Energy, and Amino Acid Digestibility in Distillers Dried Grains with Solubles in Chicks." *Poult. Sci.* 85: 470–475.

Martinez-Amezcua, C., C.M. Parsons, V. Singh, R. Srinivasan, and G. S. Murthy. 2007. "Nutritional Characteristics of Corn Distillers Dried Grains with Solubles as Affected by the Amounts of Grains versus Solubles and Different Processing Techniques." *Poult. Sci.* 86: 2624–2630.

Martinez Amezcua, C., and C.M. Parsons. 2007. "Effect of Increased Heat Processing and Particle Size on Phosphorus Bioavailablility on Corn Distillers Dried Grains with Solubles." *Poult. Sci.* 86:331–337.

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." *Poult. Sci.* 83:971–976.

Matterson, L.D., J. Tlustohowicz, and E.P. Singsen. 1966. "Corn Distillers Dried Grains with Solubles in Rations for High-Producing Hens." *Poult. Sci.* 45: 147–151.

Morrison, F.B. 1954. *Feeds and Feeding: A Handbook for the Student and Stockman*, 21th ed. Ithaca, NY: The Morrison Publishing Company.

National Research Council (NRC). 1980. *Mineral Tolerance of Domestic Animals.* Washington, DC: National Academies Press.

———. 1994. *Nutrient Requirements of Poultry*, 9th ed. Washington, DC: National. Academies Press.

Noll, S.L., J. Brannon, and C. Parsons. 2007. "Nutritional Value of Corn Distiller Dried Grains with Solubles (DDGs): Influence of Solubles Addition." *Poult. Sci.* 86 (Suppl. 1): 68.

Noll, S.L., C. Parsons, and W. Dozier III. 2007. "Formulating Poultry Diets with DDGS – How Far Can We Go? In *Proceedings of the 5th Mid-Atlantic Nutrition Conference,* pp. 91–99. N.G. Zimmerman, ed. College Park, MD: Maryland Feed Industry Council and Dept. of Animal and Avian Sciences, University of Maryland.

Noll, S.L., V. Stangeland, G. Speers, C. Parsons, and J. Brannon. 2002. "Utilization of Canola Meal and Distillers Grains with Solubles in Market Turkey Diets." *Poult. Sci.* 81(Suppl. 1): 92.

Nyachoti, C.M., J.D. House, B.D. Slominski, and I.R. Seddon. 2005. "Energy and Nutrient Digestibilities in Wheat Dried Distiller's Grains with Solubles Fed to Growing Pigs." *J. Sci. Food Agr.* 85: 2581–2586.

Ouart, M.D., D.E. Bell, D.M. Janky, M.G. Dukes, and J.E. Marion. 1988. "Influence of Source and Physical Form of Xanthophyll Pigment on Broiler Pigmentation and Performance." *Poult. Sci.* 67: 544–548.

Parsons, C.M., C. Martinez, V. Singh, S. Radhakrishman, and S. Noll. 2006. "Nutritional Value of Conventional and Modified DDGS for Poultry." Presented at the Multi-State Poultry Nutrition and Feeding Conference, Indianapolis, IN. http://www.ddgs.umn.edu/articles-poultry/2006-Parsons-%20Nutritional%20value%20of%20conventional--.pdf (accessed May 14, 2008).

Pineda, L., S. Roberts, B. Kerr, R. Kwakkel, M. Verstegen, and K. Bregendahl. 2008. "Maximum Dietary Content of Corn Dried Distiller's Grains with Solubles in Diets for Laying Hens: Effects on Nitrogen Balance, Manure Excretion, Egg Production, and Egg Quality." Iowa State University Animal Industry Report 2008, Iowa State University. http://www.ans.iastate.edu/report/air/ (accessed September 2008).

Poet Nutrition. 2007. Dakota Gold BPX. Company brochure. http://www.poetenergy.com/files/division_files/Dakota%20Gold%20AS%20Brochure%202007-1%20FEB%2026,%202007.pdf (accessed December 10, 2007).

Poet Nutrition. 2008. Dakota Gold products. Product overview, company Web site. http://www.dakotagold.com/products/ (accessed May 15, 2008).

Roberson, K.D. 2003. "Use of Distiller's Grains with Solubles in Growing-Finishing Diets of Turkey Hens." *Int. J. Poult. Sci.* 2: 389–393.

Roberson, K.D., J.L. Kalbfleisch, W. Pan, and R.A. Charbeneau. 2005. "Effect of Corn Distiller's Dried Grains with Solubles at Various Levels on Performance of Laying Hens and Egg Yolk Color." *Int. J. Poult. Sci.* 4: 44–51.

Roberts, S.A., H. Xin, B.J. Kerr, J.R. Russell, and K. Bregendahl. 2007a. "Effects of Dietary Fiber and Reduced Crude Protein on Ammonia Emission from Laying-Hen Manure." *Poult. Sci.* 86: 1625-1632.

———. 2007b. "Effects of Dietary Fiber and Reduced Crude Protein on Nitrogen Balance and Egg Production in Laying Hens." *Poult. Sci.* 86: 1716–1725.

Rostagno, H.S. 2005. Brazilian tables for poultry and swine. Composition of Feedstuffs and Nutritional Requirements, 2nd ed. Departamento de Zootecnia, Universidade Federal de Vicosa, Brazil.

Rostagno, H.S., and J.M.R. Pupa. 1995. "Diet Formulation for Broilers Based on Total Versus Digestible Amino Acids." *J. Appl. Poult. Res.* 4: 293–299.

Scheideler, S.E., M. Masa'dah, and K. Roberson. 2008. "Dried Distillers Grains with Solubles in Laying Hens Ration and Notes about Mycotoxins in DDGS." In *Pre-Show Nutrition Symposium,* Midwest Poultry Federation Convention, March 18–20, 2008, St. Paul, MN.

Sibbald, I.R. 1976. "A Bioassay for True Metabolizable Energy in Feedingstuffs." *Poult. Sci.* 55: 303–308.

———. 1986. "The T.M.E. System of Feed Evaluation: Methodology, Feed Composition Data and Bibliography." Technical Bulletin 1986-4E, Animal Research Centre, Agriculture Canada, Ottawa, ON.

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: 2639–2645.

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.

Summers, J.D. 1993. "Reducing Nitrogen Excretion of the Laying Hen by Feeding Lower Crude Protein Diets." *Poult. Sci.* 72: 1473–1478.

Thacker, P.A., and G.P. Widyaratne. 2007. "Nutritional Value of Diets Containing Graded Levels of Wheat Distillers Grains with Solubles Fed to Broiler Chicks." *J. Sci. Food Agr.* 87: 1386–1390.

University of Minnesota, Department of Animal Science. 2008a. Overview. Distillers Grains By-Products in Livestock and Poultry Feeds Web site. http://www.ddgs.umn.edu/overview.htm (accessed May 13, 2008).

———. 2008b. "Proximate Analysis of Distiller's Dried Grains with Solubles (DDGS). Nutrient Profiles—Comparison Tables. Distillers Grains By-Products in Livestock and Poultry Feeds Web site. http://www.ddgs.umn.edu/profiles/us-profile%

20comparison%20tables%20July%202008.pdf (accessed September 2, 2008).
U.S. Department of Agriculture (USDA). 2007. USDA agricultural projections to 2016. http://www.ers.usda.gov/publications/oce071/oce20071.pdf (accessed May 12, 2008).
U.S. Department of Agriculture, Economic Research Service (USDA-ERS). 2008. Feed grains database. http://www.ers.usda.gov/data/feedgrains/StandardReports/YBtable4.htm (accessed May 12, 2008).
U.S. Grains Council. 2008. DDGS User Handbook. http://www.grains.org/galleries/DDGS%20User%20Handbook/DDGS%20Handbook%20FULL.pdf (accessed June 17, 2008).
Waldroup, P.W., J.A. Owen, B.E. Ramsey, and D.L. Whelchel. 1981. "The Use of High Levels of Distillers Dried Grains plus Solubles in Broiler Diets." *Poult. Sci.* 60: 1479–1484.
Waldroup, P.W., Z. Wang, C. Coto, S. Cerrate, and F. Yan. 2007. "Development of a Standardized Nutrient Matrix for Corn Distillers Dried Grains with Solubles." *Int. J. Poult. Sci.* 6: 478–783.
Wang, Z., S. Cerrate, C. Coto, F. Yan, and P.W. Waldroup. 2007a. "Effect of Rapid and Multiple Changes in Level of Distillers Dried Grain with Solubles (DDGS) in Broiler Diets on Performance and Carcass Characteristics." *Int. J. Poult. Sci.* 6: 725–731.
———. 2007b. "Use of Constant or Increasing Levels of Distillers Dried Grains with Solubles (DDGS) in Broiler Diets." *Int. J. Poult. Sci.* 6: 501–507.
———. 2007c. "Utilization of Distillers Dried Grains with Solubles (DDGS) in Broiler Diets Using a Standardized Nutrient Matrix." *Int. J. Poult. Sci.* 6: 470–477.
Whitney, M.H., G.C. Shurson, L.J. Johnston, D.M. Wulf, and B.C. Shanks. 2006. "Growth Performance and Carcass Characteristics of Grower-Finisher Pigs Fed High-Quality Corn Distillers Dried Grain with Solubles Originating from a Modern Midwestern Ethanol Plant." *J. Anim. Sci.* 84: 3356–3363.
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.* 86: 1819–1831.