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Review

Formulation of Broiler Chicken Feeds Using Distillers Dried Grains with Solubles

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Abstract: Distillers dried grains with solubles (DDGS) is a coproduct of corn-based ethanol production that can be a valuable source of energy, digestible amino acids, and available phosphorus in poultry feeds. Dietary incorporation of DDGS reduces the amount of primary ingredients such as corn and soybean meal needed to formulate poultry diets, improving the sustainability of both biofuel and poultry production. The nutritional value of DDGS has been extensively evaluated since it became increasingly available to feed producers in the early 2000s, but evolving methods of ethanol production and coproduct fractionation necessitate its continued characterization. Attempts to relate nutrient utilization of DDGS to its chemical composition have revealed that fiber content is a primary determinant of dietary energy value of DDGS for poultry. Distillers corn oil, which is extracted from thin stillage during production of distillers grains, can also be supplemented into poultry diets as an energy-dense lipid source in place of animal fats or other vegetable-based oils. Poultry feeding practices in the United States are also evolving, including increased adoption of all vegetable-based diets and reduced use of in-feed antimicrobials. Therefore, further characterization of both the nutritional value of DDGS and its impact on gastrointestinal health will support its continued use in poultry diets.

Keywords: distillers dried grains with solubles; distillers corn oil; poultry nutrition; energy; amino acids

1. Introduction

Poultry meat and eggs serve a critical role in meeting the demand for increasing global protein consumption. Indeed, an analysis of data from the Food and Agriculture Organization of the United Nations by Henchion et al. [1] revealed that per capita and total global consumption of poultry meat increased by approximately 77% and 126%, respectively, from 1900 to 2009. Feed is the greatest input cost of poultry meat production and can account for 50–70% of total live production costs [2]. Poultry feeds are largely comprised of grains and oilseed meals, and as such, the environmental sustainability of poultry production is directly related to the efficiency by which poultry utilize nutrients within these feedstuffs. Therefore, increasing the capacity of poultry to convert agricultural coproducts that are not suited for human consumption into edible protein will be essential in sustainably meeting growing global animal protein demands.

Biofuel production in the United States, especially corn-based ethanol production, increased rapidly beginning in 2005 when legislation was enacted in an attempt to reduce reliance on petroleum-based fuels. Consequently, the amount of corn grown in the United States used for fuel ethanol production increased from 33.5 million MT in 2005 to 127 million MT in 2011, with approximately 140 million MT of corn used to produce ethanol in 2017 [3]. The production of ethanol from corn results in various coproducts that have considerable value as feed ingredients for livestock and poultry. In dry-grind, corn-based ethanol production, the starch from corn is

fermented to produce ethanol and the remaining corn fractions (protein, fat, fiber, and minerals) are concentrated, dried, and combined into a product known as distillers dried grains with solubles (DDGS). Distillers dried grains with solubles is the most commonly used ethanol coproduct in poultry feeds and serves as a source of dietary energy, digestible amino acids, and bioavailable phosphorus. Hence, the effective use of DDGS can reduce the amount of corn, soybean meal, and inorganic phosphorus needed to balance a typical US broiler chicken diet, often making it a cost-effective alternative to these primary feed ingredients.

The rapid increase in the availability of DDGS led to a considerable amount of interest and research on its use in poultry diets over the last 15 years, which has been summarized in several review papers [4–6]. Much of this work focused on quantifying the amount and availability of key nutrients within individual sources of DDGS and establishing maximum dietary inclusion levels that can support adequate poultry performance. A key concern regarding the use of DDGS in poultry diets has traditionally been the inconsistent nutrient content and availability that can exist among DDGS sources, which is largely a result of variable feedstock corn composition and processing conditions [7]. In practice, poultry nutritionists can manage the potential nutrient variability of DDGS by limiting its dietary inclusion rate and using conservative nutrient matrix values in feed formulation, but these precautions can diminish the true value of DDGS as a feed ingredient.

Most animal nutrition research has been conducted with DDGS samples containing 10–14% crude fat (ether extract (EE)), but within the last five years, the majority of ethanol producers have incorporated technology to extract additional oil from thin stillage during the DDGS production process [8]. The extracted distillers corn oil (DCO) is marketed as feedstock for biodiesel production and a valuable supplemental lipid source for swine and poultry feeds. Consequently, the energy content of the resulting reduced-oil DDGS is considered to be potentially lower and more variable than that of DDGS produced before oil extraction was widely adopted [8]. This has necessitated further research on the nutritional value of both DCO and reduced-oil DDGS as feed ingredients for poultry.

The routine use of antibiotics for growth-promotion in poultry production has been scrutinized by consumers, and poultry producers have responded with extensive efforts to eliminate antibiotic use from all stages of production (e.g., hatchery and feed) except in the response to disease outbreak. Consequently, much attention is being given to the interaction between nutritional programs and the gastrointestinal health of poultry. Therefore, the continued use of DDGS in poultry feeds will not only be based on its value as defined by traditional nutritional characterization but also by a further understanding of its use in antibiotic-free production systems. This review will highlight research relevant to the use of current generation DDGS and DCO in poultry feeds, with a primary focus on broiler chickens reared for meat production.

2. Energy and Amino Acid Utilization of DDGS by Poultry

2.1. Energy

Poultry feeds are currently formulated based on the amount of metabolizable energy (ME) within each constituent ingredient, which is defined as the energy that is digested, absorbed, and not excreted in urine. Gross energy is the total amount of energy within a feedstuff and can be easily measured by bomb calorimetry, but ME values of a feed ingredient must be determined using an in vivo feeding trial. There is little standardization among assays to determine ME of feedstuffs for poultry [9], but values are typically determined in either adult roosters or growing broiler chickens and each approach has both advantages and disadvantages. Metabolizable energy values determined in adult roosters are often corrected for endogenous energy losses using fasted roosters and termed "true" ME (TME) values, whereas values determined in growing broilers that are not corrected for endogenous energy losses are referred to as "apparent" ME (AME) values. These estimates are usually corrected to account for differences in nitrogen retention among birds used in the assay and subsequently presented as nitrogen-corrected TME (TME_n) and AME (AME_n) values.

Batal and Dale [10] were the first to publish an extensive characterization of TME_n values for a range of DDGS samples. The composition (86% dry-matter (DM) basis) of these samples ranged from 23.0% to 30.0% crude protein, 2.5% to 10.6% crude fat, 5.1% to 8.1% crude fiber, and 3.9% to 5.4% ash, and rooster feeding assays yielded TME_n values that averaged 2820 kcal/kg and ranged from 2490 to 3190 kcal/kg. Parsons et al. [11] used a similar rooster assay to evaluate 20 DDGS samples that contained 13–16% crude fat and 3.7–4.4% ash (fiber analyses not reported) and found that TME_n ranged from 2607 to 3054 kcal/kg and averaged 2863 kcal/kg (as-is basis, 88% mean DM). Using adult cecectomized roosters, Fastinger et al. [12] reported the average TME_n (as-fed basis) of five DDGS samples to be 2871 kcal/kg and range from 2484 and 3014 kcal/kg. While these values serve as good reference points on the amount and variability of energy within DDGS, the samples evaluated by these authors were of earlier generation with compositions not totally reflective of currently available DDGS. Indeed, the weighted mean TME_n (3265 kcal/kg, DM basis) for the older generation samples in the aforementioned reports is higher than the weighted mean AME_n (2563 kcal/kg, DM basis) reported in more recent papers (Table 1). This difference could be partly due to the typically lower EE content reported for these newer generation samples, variations in bird type used to generate the ME values (i.e., broiler versus adult rooster), or a combination of these and other factors.

Table 1. Nutrient composition and energy content (dry-matter basis) of corn distillers dried grains with solubles summarized from selected papers reporting nitrogen-corrected apparent metabolizable energy (AME_n) content determined in broiler chickens.

Item, % Dry Matter Unless Noted Otherwise	Rochell et al. [13]		Meloche et al. [14]		Meloche et al. [15]		Adeola and Zhai [16]	Weighted Mean
	n = 6		*n* = 15		*n* = 15		*n* = 1	
	Mean	SD	Mean	SD	Mean	SD	Mean	
Dry matter	89.72	2.15	89.07	1.55	89.32	0.93	92.10	89.36
Crude protein	30.32	2.35	30.28	2.01	31.33	1.70	28.70	30.67
Ether extract	9.81	2.80	9.47	2.65	9.45	2.63	10.10	9.54
Total dietary fiber	34.99	2.48	33.33	2.36	31.22	2.24	NR	32.73
Neutral detergent fiber	37.78	6.63	35.72	6.14	35.14	3.94	24.83	35.52
Acid detergent fiber	11.74	2.37	11.86	2.21	10.49	1.87	8.45	11.19
Crude fiber	7.67	0.53	NR	NR	9.19	0.81	5.93	8.63
Starch	4.81	1.63	2.27	1.06	5.19	1.87	NR	3.91
Ash	4.68	0.41	4.90	0.30	5.17	0.38	NR	4.98
Gross energy, kcal/kg	5287	114	4998	108	5063	121	4762	5065
AMEn, kcal/kg	2764	363	2309	260	2676	272	2688	2563

Abbreviation: SD = standard deviation, NR = not reported.

One potential strategy to mitigate the inherent variability in ME values of DDGS is to define relationships between chemical composition and energy utilization so that energy prediction equations can be established. This approach was taken by Batal and Dale [10], who used regression analyses to determine that the analyzed concentrations of crude fat, crude fiber, crude protein, and ash could be used in an equation to predict TME_n of DDGS (TME_n = 2732.7 + (36.4 × EE, %) − (79.3 × fiber, %) + (14.5 × protein, %); R^2 = 0.45; 86% DM basis). However, these authors noted that the low R^2 values indicate that this particular equation should only be used as a general guide for assessing the TME_n content of DDGS. Furthermore, no validation experiments were conducted, leaving unknown the actual ability of this equation to accurately predict TME_n of DDGS.

To develop robust prediction equations, it is important to have a wide range in values for both the dependent (e.g., TME_n or AME_n) and independent variables (e.g., chemical composition). As such, Rochell et al. [13] used stepwise multiple linear regression to generate AME_n prediction equations based on 15 diverse corn milling coproducts that included several DDGS samples, corn germ, corn gluten feed, corn meal, and corn bran to encompass a wide range in starch, fat, fiber, protein, and ash concentrations. Metabolizable energy (AME_n, DM basis) values of these products were determined to range from 1746 kcal/kg for corn gluten feed to 3495 kcal/kg for corn germ. Using R^2

and the Mallows statistic (C(p)) as best-fit criteria, two AME_n prediction equations reported by these authors were:

$$AME_n \text{ (kcal/kg, DM basis)} = 3517 + (46.02 \times \text{EE, \%}) - (82.7 \times \text{ash, \%}) - (33.27 \times \text{hemicellulose, \%}); R^2 = 0.89, C(p) = -2.57 \quad (1)$$

$$AME_n \text{ (kcal/kg, DM basis)} = (-30.19 \times \text{neutral detergent fiber, \%}) + (0.81 \times \text{GE, kcal/kg}) - (12.26 \times \text{crude protein, \%}); R^2 = 0.87 \quad (2)$$

Although Equation (1) was determined to have the best fit, Equation (2) was developed to circumvent the need for hemicellulose analysis in predicting AME_n of DDGS, as this is not a common analysis in commercial feed laboratories. Subsequent work in the same laboratory at Auburn University by Meloche et al. [14] established prediction equations from 15 DDGS samples that ranged from 3.15% to 13.23% EE and from 1869 to 2824 kcal/kg in AME_n (DM basis). Using adjusted R^2 (R^2_{adj}), the Mallows statistic (C(p)), prediction error sum of squares (PRESS), and the prediction coefficient of determination (R^2_{pred}) as best-fit criteria, two equations reported by these authors were:

$$AME_n \text{ (kcal/kg, DM basis)} = -12{,}282 + (2.60 \times \text{GE, kcal/kg}) + (89.75 \times \text{crude protein, \%}) + (125.80 \times \text{starch, \%}) - (40.67 \times \text{total dietary fiber, \%}); R^2 = 0.90, R^2_{adj} = 0.86, C(p) = 2.58, PRESS = 199{,}819 \quad (3)$$

$$AME_n \text{ (kcal/kg, DM basis)} = -14{,}322 + (2.69 \times \text{GE, kcal/kg}) + (117.8 \times \text{crude protein, \%}) + (149.41 \times \text{starch, \%}) - (18.30 \times \text{NDF, \%}); R^2 = 0.92, R^2_{adj} = 0.88, C(p) = 1.35, PRESS = 227{,}477 \quad (4)$$

Again, despite the better internal fit of Equation (3), Equation (4) was presented due to its inclusion of neutral detergent fiber rather than total detergent fiber, which is more technically complex to measure and not routinely used in commercial feed laboratories.

Meloche et al. [15] subsequently conducted a validation experiment in which predicted AME_n from the four equations above was compared with observed AME_n for 15 external DDGS samples, which ranged from 1975 to 3634 kcal/kg (DM basis). These authors demonstrated that Equations (1) and (2) were found to be slightly more predictive than Equations (3) and (4), as indicated by root-mean-square error values of the differences between observed and predicted AME_n. Furthermore, these authors generated a fifth equation in which nutrient values from proximate analysis of 30 corn coproducts reported by both Rochell et al. [13] and Meloche et al. [14] were entered into a regression model, and the least absolute shrinkage and selection operator technique was used determine a best fit equation based on routinely measured DDGS components:

$$AME_n \text{ (kcal/kg, DM basis)} = 3673 - (121.35 \times \text{crude fiber, \%}) + (51.29 \times \text{EE, \%}) - (121.08 \times \text{ash, \%}); R^2 = 0.70, R^2_{adj} = 0.67, C(p) = 0.62 \quad (5)$$

Importantly, Meloche et al. [15] concluded that the error associated with all five of the equations presented above may be beyond what is acceptable for use in practical feed formulation. Nonetheless, these equations provide valuable information on the chemical fractions that most likely influence energy utilization of DDGS, which most consistently appeared to be various measures of fiber. Surprisingly, EE was only found to be a predictive independent variable in Equation (1), with the exception of Equation (5), which was generated using a regressor pool that was limited only to crude fiber, EE, ash, and crude protein. Indeed, simple linear regression of AME_n on EE content for 36 DDGS samples evaluated by Rochell et al. [13] and Meloche et al. [14,15] indicates that EE content alone accounted for less than 20% of the total variability in the AME_n content of DDGS for broilers (Figure 1). Wang et al. [17] recently reported that a combination of gross energy and neutral detergent fiber provided the best fit for AME_n prediction in late-cycle laying hens fed DDGS samples selected to vary

in EE content (2.18–17.78%, DM basis). While these authors did not determine EE to be a significant predictor of AME_n, gross energy content of DDGS was found to be highly correlated with EE (r = 0.91). Similarly, a correlation between EE and GE was reported by Meloche et al. [14] (r = 0.74), although no correlation between GE and EE was found by Rochell et al. [13]. Consequently, collinearity among regressors used for AME_n prediction should be considered in interpreting these equations.

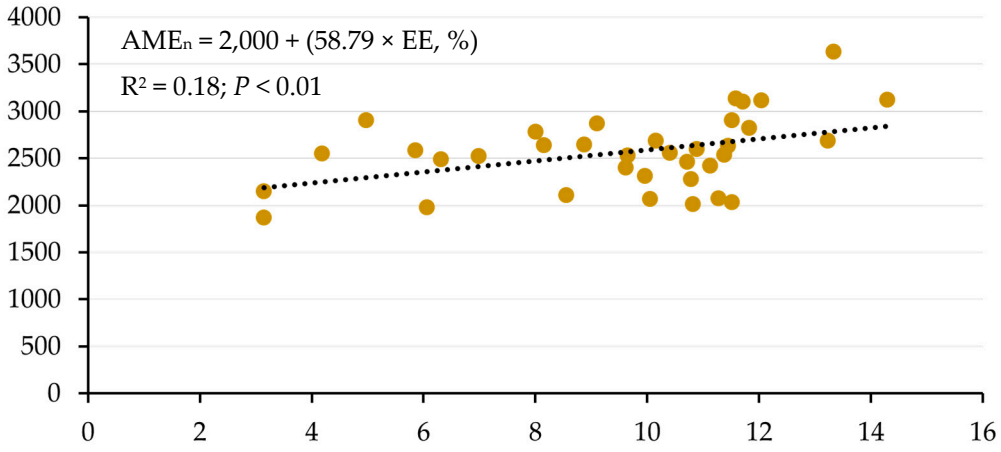

Figure 1. Linear regression of nitrogen-corrected apparent metabolizable energy (AME_n, kcal/kg, dry-matter basis) determined in broiler chickens on ether extract (EE) content (%, dry matter basis) of 36 samples of distillers dried grains with solubles. Data from Rochell et al. [13] and Meloche et al. [14,15].

It appears that improved energy utilization of DDGS by poultry will likely be realized through further fractionation or enzymatic degradation of fiber (nonstarch polysaccharides (NSP)) during their production, or alternatively, by advancements in technology to improve the capacity of poultry to degrade and ferment NSP in vivo. The latter approach is currently targeted through the use of exogenous feed-grade NSP-degrading enzymes, as extensively reviewed by Swiatkiewicz et al. [18]. Nonstarch polysaccharides within DDGS exist in matrices with starch and protein, so NSP degradation via exogenous enzymes can also release other nutrients for subsequent digestion and absorption [19]. A novel approach of using a direct-fed microbial containing *Bacillus* strains selected on qualitative enzyme activity was shown to improve intestinal morphology and performance of broilers fed a diet containing 8% DDGS, which could have resulted from the diversity of enzymes produced by the direct-fed microbial [20]. In contrast, exogenous protease addition decreased the ability of a multicarbohydrase to degrade the DDGS fiber–starch–protein matrix in vitro, possibly due to its degradation of exogenous and microbially derived carbohydrases [19]. Thus, although a multienzyme approach to simultaneously target numerous substrates is likely the most promising approach, additional research is still needed to fully to maximize energy and nutrient utilization of DDGS using feed-grade exogenous enzymes.

2.2. Amino Acids

In the United States, poultry diets are almost exclusively formulated based on the digestible amino acid content of constituent feedstuffs rather their crude protein content. In a typical broiler feed based on corn and soybean meal, the amount of lysine, methionine, and threonine contributed by these two ingredients will not meet the requirements of the bird [21], and as such, these amino acids are routinely supplemented in poultry feeds. This warrants rigorous monitoring of the concentration and digestibility of these economically important amino acids in potential feed ingredients. As discussed for metabolizable energy assays, the methodology to determine amino acid digestibility of feedstuffs also varies considerably, and digestibility values are routinely generated using both roosters and growing

broilers. Amino acid digestibility values of DDGS can differ among classes of poultry, so specific values according to production purpose may improve the accuracy of feed formulations [22,23].

The amino acid profile of DDGS is largely reflective of that of corn, which has a low lysine content relative to its crude protein content, but it also contains protein from the yeast used in upstream fermentation [24]. Lysine digestibility of DDGS is a primary concern of poultry nutritionists due to the susceptibility of this amino acid to Maillard reactions during the drying process of DDGS, which can reduce both the concentration and digestibility of lysine [25]. Accordingly, the digestibility of lysine in DDGS ranges from approximately 50% to 65% in broilers, compared with approximately 89% Lys digestibility observed for soybean meal [23,26,27]. Dozier et al. [27] evaluated the ileal amino acid digestibility of DDGS containing 5.43%, 7.87%, and 10.52% EE and found that lysine digestibility of the 10.52% EE sample was higher than that of the 7.87% and 5.43% EE samples, indicating that oil extraction of DDGS has the potential to influence amino acid digestibility. However, when these authors accounted for the higher lysine concentration of the reduced-oil samples, the digestible lysine content (i.e., concentration × digestibility) was similar across all three samples. Therefore, the potential for oil extraction during DDGS production to influence both the concentration and digestibility of amino acids must be taken together to determine the overall effect on amino acid quality of the final product.

3. Influence of DDGS on Live Performance and Processing Characteristics of Broiler Chickens

Following widespread adoption of oil extraction from DDGS, the influence of reduced- and low-oil DDGS on poultry performance, body composition, and meat yield became a critical research question. Guney et al. [28] fed 10% or 20% of DDGS containing 12.45%, 7.52%, or 6.74% EE to male broilers from 0 to 18 days of age. Prior to the growth trial, TME_n values of the three DDGS were determined, whereas previously published values of TME_n were used for other ingredients and for amino acid digestibility values for all ingredients. Final body weights at 18 days of age were highest for birds fed diets with 12.45% or 6.74% EE DDGS at a 10% inclusion level, whereas body weights were generally lower and not different among birds fed the three sources at a 20% dietary inclusion. Broilers fed a 20% inclusion of DDGS had reduced feed efficiency compared with those fed 0% or 10% DDGS, regardless of oil content. Cortes-Cuevas [29] incorporated 6% or 12% of two DDGS samples containing 6.54% or 5.39% EE into diets based on sorghum and soybean meal fed to broilers reared sex-separately from 0 to 42 days posthatch and found no differences in live performance or processing characteristics among dietary groups. Kim et al. [30] sought to establish the maximum amount of reduced-oil DDGS that could be fed to broilers during the finisher 1 (28–42 days posthatch) and finisher 2 (42–56 days posthatch) periods when the birds were grown to market weights greater than 3.0 kg. Digestible amino acid values of the DDGS sample (7.42% EE) used in feed formulation were estimated using near infrared reflectance spectroscopy, whereas AME_n was determined in a preliminary in vivo trial. From 28 to 42 days posthatch, body weight gain and carcass yield decreased linearly, while feed conversion ratio increased as DDGS inclusion increased from 0% to 30%. Although dietary crude protein content increased with DDGS inclusion and all diets were balanced for digestible concentrations of lysine, total sulfur amino acids, threonine, isoleucine, and valine, it is possible that amino acid digestibility of the DDGS was overestimated by near infrared reflectance spectroscopy, or that increased DDGS resulted in dietary limitations of other essential amino acids such as tryptophan or arginine. In a subsequent experiment evaluating diets containing 0%, 6%, 12%, 18%, or 24% of the same DDGS when fed to broilers from 43 to 56 days posthatch, no effects on live performance or processing characteristics were observed [30]. Thus, it is possible that the older broilers had a greater capacity to handle the higher fiber diets, or that the amino acid profile of the diets was more suitable for the birds during that rearing period [30].

In two separate reports, Dozier et al. [31,32] used previously characterized AME_n and amino acid digestibility values for three DDGS samples (5.4%, 7.8%, or 10.5% EE) to formulate two diet series based on conventional or increased DDGS inclusion programs. In a 33-day trial using three

feeding phases, the conventional feeding program included 5%, 7%, and 9% of the three DDGS sources in the starter, grower, and finisher diets, respectively, whereas the increased programs included 8%, 10%, and 12% DDGS in the same phases [31]. The increased inclusion program reduced overall body weight gain by 3% and increased feed conversion ratio, but these measurements were not different among the DDGS sources. While inclusion program × DDGS oil content interactions were observed for carcass and breast meat yields, the final weights of these parts were not impacted. In a 49-day trial using four feeding phases, the conventional feeding program included 5%, 7%, 9%, and 11% of the three DDGS sources in the starter, grower, finisher 1, and finisher 2 diets, respectively, whereas the increased programs included 8%, 10%, 12%, and 14% DDGS in the same phases [32]. Overall body weight gain, feed conversion ratios, and meat yield were not influenced by DDGS source or inclusion program. Using ingredient prices available at that time, it was reported that diet cost per unit of body weight gain was $0.025/kg higher for birds fed the 5.4% EE DDGS compared with those fed the 10.5% product due to the higher amount of supplemental fat required to formulate the diets to be isocaloric.

In each performance trial mentioned above, increased DDGS inclusion simultaneously reduced the amount of primary cereal grain (corn or sorghum), soybean meal, and inorganic phosphorus required to balance each diet, whereas the amount of supplemental lysine and added fat typically increased. Therefore, the value and extent to which least-cost feed formulation software incorporates DDGS into the diet will be directly influenced by the market prices of these ingredients as well as the nutrient matrix values applied to each. Other factors such as handling and feed milling characteristics will also continue to be considered by nutritionists in establishing the value and maximum inclusion levels of DDGS for each production scenario.

4. Distillers Corn Oil as a Feed Ingredient for Poultry

Oil extraction during production of distillers grains has led to increased availability of DCO as a supplemental source of lipids in livestock feeds [8]. Distillers corn oil has a desirable fatty acid profile for poultry, as it primarily contains unsaturated fatty acids, and in particular, has a high concentration of linoleic acid (>50%) [33], which is the only essential fatty acid typically monitored during poultry diet formulation. Furthermore, DCO is compatible with all-vegetable-based diets, which are being increasingly adopted by the poultry industry. The average lipid digestibility and AME_n values of three DCO sources were found to be 84.4% and 7889 kcal/kg (as-is basis), respectively, and did not differ within the range of free fatty acids typically found (<15.0%) in commercially available DCO [33]. Complete replacement of poultry fat with DCO on a weight basis with no adjustment in ingredient or dietary AME_n values did not influence the overall body weight gain, feed conversion, or meat yield of broilers grown to 48 days posthatch, and there appeared to be synergistic effects between fat sources when using a blend of 75% poultry fat and 25% DCO for birds up to 35 days [34]. Interestingly, these authors also reported that pellet quality was improved as DCO replaced poultry fat.

In many countries, yellow skin pigmentation is a highly desirable trait for poultry products and several commercial pigmentation products are used to increase the dietary carotenoid intake of broilers and layers. Similar to other nutrients, carotenoids naturally found within corn are concentrated in DDGS. Indeed, higher yellowness vales for skin and abdominal fat were determined for broilers fed a diet with 12% DDGS compared with those fed the control diet (0% DDGS), reflecting the bioavailability of DDGS-derived carotenoids [29]. Carotenoids, which are fat soluble, are found in high concentrations in DCO, and DCO-derived carotenoids have been reported to have a bioavailability similar to that of commercially available pigmentation products [35]. Thus, in addition to serving as a concentrated energy source, DCO may be a suitable ingredient to increase poultry skin and egg pigmentation when desired for certain markets.

5. The Impact of DDGS on Gastrointestinal Health of Poultry

The US poultry industry has made a substantial shift away from the use of antibiotics within the live production chain. In fact, approximately 40% of US broilers are currently reared using

antibiotic-free production practices [2]. Consequently, considerable focus is being placed on the challenge of maintaining gastrointestinal health in broilers without the use of in-feed antibiotics. A plethora of feed additives are available as potential alternatives to antibiotics, but successful antibiotic-free production requires systematic changes to both bird management and nutritional programs. Ingredient quality and digestibility are key factors in this regard, as fermentation of undigested macronutrients, particularly protein, in the hindgut can exacerbate gastrointestinal stress and disease [36].

The yeast fermentation process used to produce DDGS results in a meaningful but difficult to quantify fraction of dead yeast cells within DDGS [37]. Yeast and yeast derivatives can have a variety of benefits as feed ingredients for food animal health and production, including enhanced intestinal microflora and immunocompetence, increased nutrient digestibility, and improved feed efficiency, as extensively reviewed by Vohra et al. [38]. It is likely that many of the benefits derived from feeding concentrated yeast cell wall components such as mannan-oligosaccharides, β-glucans, and nucleotides are inherent to DDGS as well, but limitations in accurately characterizing these components within DDGS make it difficult to fully determine their effects on animal health and performance [37]. In addition to residual yeast, fiber degradation of DDGS achieved through dietary enzyme or direct-fed microbial supplementation may release carbohydrates with functional or prebiotic properties [39], but this hypothesis needs further validation in poultry.

Experimental data regarding the interaction between corn DDGS and gastrointestinal health in poultry are relatively sparse. Perez et al. [40] reported that feeding 10% or 20% DDGS did not influence the severity of coccidiosis infection in broilers but potentially shifted the ileal microbiota towards a more beneficial composition. Similarly, Abudabos et al. [41] found that increasing DDGS up to 24% of the diet was associated with an increased richness index of the cecal microbiota, indicating a greater diversity of bacteria, which is generally considered a benefit to gastrointestinal health. On the other hand, these authors reported that increasing DDGS inclusion reduced the population of *Faecalibacterium*, a genus of bacteria that typically responds positively to increasing dietary fiber and is considered beneficial for gastrointestinal health. Using a necrotic enteritis challenge model in which broilers were inoculated with *Clostridium perfringens*, Alizadeh et al. [42] found that challenged birds fed a diet containing 10% corn–wheat DDGS had similar growth performance, mortality, lesion scores, and ileal *Clostridium perfringens* counts compared with those fed a control diet without DDGS. Therefore, current data indicate that DDGS inclusion levels routinely used in commercial poultry feeds may have minimal impact on the severity of some gastrointestinal diseases commonly faced in the US broiler industry. However, more research is certainly needed to fully define the interactions between DDGS and gastrointestinal health and subsequent effects on bird performance.

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