CHAPTER 19

Pelleting DDGS Diets for Poultry

Introduction

ALTHOUGH DDGS IS AN ECONOMICAL ENERGY AND DIGESTIBLE NUTRIENT SOURCE in poultry diets, diet inclusion rates are often limited to less than 10 percent of the diet because of concerns of achieving desired pellet quality and pellet mill throughput. As a result, the ability of feed manufacturers and poultry producers to capture greater economic value from using higher dietary inclusion rates is diminished because of the diet inclusion constraints imposed on DDGS to meet desired pellet quality and production efficiencies in commercial feed mills.

Pelleting is the most common thermal processing method used in manufacturing poultry feeds (Abdollahi et al., 2013), and provides the advantage of improved feed conversion resulting from reduced feed wastage and improved digestibility of energy and nutrients which has partially been attributed to the partial gelatinization of starch (Richert and DeRouchey, 2010; NRC, 2012). Additional advantages of pelleting diets include reduced dustiness, ingredient segregation during transport, pathogen presence and sorting large particles in mash, along with improved palatability, bulk density and handling characteristics (Abdollahi et al., 2012; NRC, 2012).

Pelleting Processes

Pelleting is a mechanical process that agglomerates small particles into larger particles using moisture, heat and pressure (Falk, 1985). Commercial pellets can be manufactured to have a wide range of diameters (0.16 mm to 0.75 mm), shapes (triangular, square, oval or cylindrical) and sizes depending the intended animal species and feeding application (California Pellet Mill Co., 2016).

The first step in producing pelleted feeds is particle size reduction of ingredients (primarily grains) using a hammer mill or roller mill. Generally, diets to be pelleted have lower average particle size than those fed in meal or mash form to increase pellet durability (Wondra et al., 1995). Next, ingredients are individually weighed and added to mixers in the desired proportions based on the formulation, and mixed for an appropriate amount of time to achieve a homogeneous mixture. The resulting mash is then subjected to steam-conditioning, in which steam is used to provide the proper balance of heat and moisture (Smallman, 1996). Although steam conditioning requires energy and contributes to the cost of the pelleting process, it increases pellet production rates and pellet durability index (PDI) compared with dry-conditioning (Skoch et al., 1981). After steam is applied to the mash inside the conditioner, the moist, hot mash flows into the pelleting chamber where it passes through a metal die to form pellets. As the pellets exit the die, they enter a cooler to reduce their temperature from 80 to 90°C down to 8°C above ambient temperature (Zimonja et al., 2007), along with reducing moisture from 15 to 17 percent down to 10 to 12 percent using a stream of ambient air (Robinson, 1976). Fines collected in the cooler are returned to the pellet chamber to be subsequently reformed into pellets. For some poultry feeding applications, the cool dry pellets pass through a crumbler to form crumbles (broken pellets).

Factors Affecting Pellet Durability, Energy Consumption and Production Rate

The three main goals of manufacturing high-quality pelleted poultry diets are to achieve high pellet durability and pellet mill throughput, while minimizing energy cost of the pelleting process (All About Feed, 2012). In general, achieving high pellet durability increases the likelihood pellets will remain intact from the time of manufacturing until they are consumed by birds. However, almost any adjustment made to increase pellet durability decreases pellet mill throughput and increases energy cost (Behnke, 2006). Producing a high-quality pellet is influenced by factors such as type of feed, quantity of lipid, steam additives, particle size, moisture content, die quality, roller quality and the gap between the roller and the die (California Pellet Mill Co., 2016). The primary contributors to energy use and cost during the pelleting process are the production of steam for the conditioning stage, and electricity (measured in kilowatt hours per ton) required to operate the feeders, conditioners, pellet mill and pellet cooling system. Most (up to 72 percent) of the energy used for pelleting is for steam conditioning (Skoch et al., 1983), and Payne (2004) suggested that 10 kilowatt hours per metric ton should be a reasonable goal for pelleting broiler diets, respectively. In fact, effective decision support systems have been developed to optimize pellet quality, production rate and cost while only slightly decreasing pellet durability (Thomas et al., 1997).

Characteristics of the pellet die affect pellet durability, mill throughput, and energy consumption and include: metal properties, hole design, hole pattern and number of holes (Stark, 2009). The types of metals in the die affect the amount of friction generated and subsequent temperature increases as the mash passes through the die (Behnke, 2014). Hole design can be straight bore or relief, but the most important factor related to a pellet die is the thickness (L) of die relative to hole diameter (D), commonly described as the L to D ratio or L:D. As the L to D ratio increases (thicker die), pellet durability increases due to increased friction and die retention time, but pellet mill throughput is reduced and energy consumption is increased (Traylor, 1997).

Physical pellet quality refers to the ability of pellets to remain intact during bagging, storage and transport until reaching the feeders in the animal production facility, while minimizing the proportion of fines (Cramer et al., 2003; Amerah et al., 2007). Pellet quality is commonly measured by the pellet durability index (PDI; ASAE, 1997). There are five binding mechanisms important to achieve a high PDI and include: forming solid bridges, attraction forces between solid particles, mechanical interlocking bonds, adhesion and cohesion forces, as well as interfacial forces and capillary pressure (Thomas and van der Poel, 1996; Kaliyan and Morey, 2006).

Similar to pellet quality, energy consumption of pellet mills depends on variables such as pellet die diameter, die speed, L to D ratio and feed ingredient moisture and chemical composition (Tumuluru et al., 2016). Electrical usage in pellet mills is quantified as units of energy per unit of throughput or time and is commonly described as kilowatt-hours per ton (kWh/ton; Fahrenholz, 2012)as well as to investigate the potential for modeling the effects of formulation and processing factors on both pellet durability index (PDI. Minimizing energy consumption per ton of pelleted feed can be achieved by maximizing the production rate, which is affected by diet characteristics and die volume (Fahrenholz, 2012)as well as to investigate the potential for modeling the effects of formulation and processing factors on both pellet durability index (PDI.

Production rate of the pellet mill is another important factor that influences PDI and energy consumption. Stark (2009) showed that increasing pellet mill throughput from 545 kg/hr to 1646 kg/hr increased pellet mill efficiency from 73.3 to 112.4 kg/horse power hour, and linearly reduced PDI from 55.4 to 30.2 percent

Steam conditioning of the mash is considered to be the most important factor in achieving high pellet durability. High conditioning temperature increases PDI and decreases energy consumption (Pfost, 1964) due to decreased mechanical friction (Skoch et al., 1981). Starch gelatinization decreases as conditioning temperature increases (Abdollahi et al., 2011). Changing the pitch of the conditioner paddles (Briggs et al., 1999) can be used to increase retention time (heat) and increase PDI (Gilpin et al., 2002). However, the effects of steam pressure on improving PDI are inconsistent. Cutlip et al. (2008) reported increasing steam pressure resulted in only small improvements in PDI, whereas Thomas et al. (1997) reported there is no clear relationship between steam pressure and PDI. This poor relationship was also observed in an earlier study where there was no effect of steam pressure on PDI or production rate (Stevens, 1987). As a result, Briggs et al. (1999) concluded that using 207-345 kilopascals appears to be sufficient steam pressure for achieving a high PDI in pellets.

Many feed manufacturers perceive that diet particle size has a significant influence on PDI of pellets, but there is no strong research evidence to support this. Theoretically, larger particles can cause fractures in the pellets making them more prone to breakage (California Pellet Mill Co., 2016). However, Stevens (1987) showed that particle size of ground corn had no effect on production rate or PDI. Similarly, Stark et al. (1994) reported reducing diet particle size from 543 to 233 microns only slightly increased PDI. Likewise, Reece et al. (1985) showed that increasing particle size of the diet from 670 to 1289 microns only slightly decreased PDI.

Although diet particle size is not a major factor in achieving desired pellet quality and manufacturing efficiency, diet composition is an important factor due to its effects on die lubrication and abrasion, as well as bulk density of the feed (Behnke, 2006). As a result, various feed ingredients have been characterized based on pelletability factors (Payne et al., 2001). While it is theoretically possible to use these relative feed ingredient pelletability factors as constraints in diet formulation, in practice this is infeasible because the primary goal in diet formulation is to meet the nutritional needs of birds at a low cost, rather than manipulating formulations to optimize PDI.

Starch content of poultry diets plays a significant role in determining the PDI after pelleting. Maximum PDI can be achieved in diets containing 65 percent starch, while low-starch diets with high-protein content decrease pellet durability (Cavalcanti and Behnke, 2005a). In fact, starch and protein content of the diet has been shown to have a greater effect on PDI than conditioning temperature (Wood, 1987). Increasing dietary lipid content decreases PDI (Cavalcanti and Behnke (2005a), and adding 1.5 percent to 3 percent fat has been shown to decrease PDI by 2 percent and 5 percent, respectively (Stark et al., 1994). Furthermore, adding fat to diets before pelleting may not always reduce energy consumption during the pelleting process because there are many interactions among chemical components of diets (Briggs et al., 1999). For example, Cavalcanti and Behnke (2005b) showed increasing protein content in corn, soybean meal and soybean oil diets increased PDI.

Moisture content of the mash is another major factor contributing to pellet durability and energy consumption during pelleting. Gilpin (2002) showed increasing mash moisture content increased PDI and reduced energy consumption. Furthermore, the addition of five percentage points of moisture to mash before pelleting has been shown to increase PDI when pelleting high fat diets (Moritz et al., 2002).

Measuring Pellet Quality

Pellet durability can be measured by a variety of tumbling tests, such as mechanical tumbling and pneumatic tumbling, and include Stoke's ® Tablet Hardness Tester, tumbling box test, and the Holman Pellet Tester (Behnke, 2001; Winowiski et al., 1962). The standard pellet durability test used in the feed industry is ASAE S269.4 (ASAE Standards, 2003). This method determines the PDI, which is defined as the percentage of whole pellets remaining after a sifted sample has been tumbled in a tumble box. Another method used with less frequency are the Homen pellet testers manufactured by TekPro (Norfolk, UK). Holmen pellet testers agitate pellets in a pyramid-shaped, perforated chamber, and fines exit the chamber over a 20- to 120-second period to be quantified. Only two studies have compared the use of the ASAE S269.4 method with the Holmen pellet testers. Winowski (1998) reported the results from both methods were correlated, and Fahrenholz (2012) also reported the results between the two methods were correlated, but showed that the use of the ASAE tumble box method provided more consistent and repeatable results for measuring PDI than the Holmen testers. Fahrenholz (2012) also showed while there were significant associations between pellet hardness, pellet density, pellet retention time and initial/ final moisture on PDI, these associations are weak and cannot be used as predictors of PDI.

Chemical Characteristics of DDGS

Changes in chemical composition of DDGS continue to evolve as the U.S. ethanol industry adopts new processes to enhance revenue from the production of ethanol and co-products. Because chemical composition of DDGS is an important factor affecting pellet quality, it is useful to understand the variability among sources and the impact of partial oil extraction. Traditionally, the nutrient composition of DDGS (Spiehs et al., 2002; Belyea et al., 2004) contained greater concentrations of crude fat, NDF and starch, but lower crude protein content than the reduced-oil DDGS currently being produced (Kerr et al., 2013; **Table 1**). However, regardless of these changes in chemical composition, DDGS has very low starch, and relatively high crude fat and NDF content compared with other common feed ingredients, which makes it challenging to when manufacturing high quality pelleted poultry feeds containing high dietary inclusion rates of DDGS, because these chemical components have negative effects on achieving the desired PDI.

California Pellet Mill Company (2016) has classified several common ingredients based on their "pelletability" characteristics. Distillers grains are classified as having low pelletability and a medium degree of abrasiveness on pellet die. There are several reasons for DDGS to be classified as low pelletability (**Table 2**). First, DDGS has relatively low moisture content which may require adding moisture to the diet in addition to steam provided in the pellet mill, to achieve a good quality pellet, but is dependent on the diet inclusion rate of DDGS and the overall moisture content of the diet. However, although the relatively high protein content of DDGS contributes to plasticizing the protein during pelleting that enhances pellet quality, the relatively high oil content in DDGS contributes toward reducing pellet quality but is dependent on diet inclusion rate and amount of other fats or oils added to complete diets. In contrast, the benefit of DDGS having a relatively high oil content is that it can contribute to improved pellet mill production rates. Some types of fiber in feed ingredients contain natural binders that contribute to good quality pellets, but ingredients like DDGS that contain relatively high amounts of fiber actually reduce

Table 1. Comparison of average, range, and changes in nutrient composition of DDGS resulting from partial oil extraction (dry matter basis)

Nutrient	Corn DDGS (>10 % oil)	Corn DDGS (<10 % oil)[3]
Moisture %	11.1 (9.8-12.8)[1]	12.5 (10.0-14.5)
Crude protein %	30.8 (28.7-33.3)[1,2]	31.2 (29.8-32.9)
Crude fat %	11.5 (10.2-12.6)[1,2]	8.0 (4.9-9.9)
NDF %	41.2 (36.7-49.1)[1]	32.8 (30.5-33.9)
Starch %	5.3 (4.7-5.9)[2]	2.4 (0.8-3.4)
Ash %	5.2 (4.3 – 6.7)[1,2]	5.4 (4.9-6.1)

[1]Spiehs et al. (2002)
[2]Belyea et al. (2004)
[3]Kerr et al. (2013)

production rates of pellet mills because fiber is difficult to compress into pellets. The starch content of DDGS is low and may be partially gelatinized during the production process, which is not conducive to improving pellet quality. Furthermore, DDGS has moderate bulk density which can contribute to reduced production rates depending on the density and amounts of other ingredients in the feed formulation. Particle size of DDGS varies from 294 to 1,078 µm among sources (Kerr et al., 2013). Fine- and medium-ground particle sizes provide more surface area for moisture absorption from steam and results in greater chemical changes which may enhance pellet quality and prevent large particles from serving as natural breaking points for producing fines. Furthermore, low- and medium-particle sized ingredients and diets may improve lubrication of the pellet die and increased production rates.

Pelleting DDGS Diets for Poultry

Benefits and limitations of pelleting poultry diets

In general, pelleting broiler diets results in improved growth performance compared with feeding mash diets. Jafarnejad et al. (2010) compared broiler growth performance when feeding crumble-pelleted vs. mash diets and showed improved body weight gain and feed conversion when birds were fed crumbles. Previous studies have also shown similar results when feeding high quality pellets to broilers (Jensen et al., 1962; Nir et al., 1994). Much of the improvement growth rate and feed conversion from feeding pellets is a result of increased feed intake (Engberg et al., 2002; Svihus et al., 2004; Abdollahi et al., 2011). Pellet quality is important to achieve optimal feed intake because as the proportion of intact pellets increases (decreased percentage of fines), feed intake and body weight gain increase (Lily et al., 2011). Furthermore, pelleting has been estimated to contribute 197 kcal/kg to diet AME_n content in 100 percent pellets (no fines), but although the AME_n content decreases as the percentage of fines increases, diets with 20 percent pellets (80 percent fines) still provides an improvement of 76 kcal/kg in AME_n (McKinney and Teeter, 2004). Similarly, Skinner-Noble et al. (2005) reported pellets increase AME_n content by 151 kcal/kg compared with feeding mash diets. Some of this improvement in energy utilization can be attributed to lower heat increment and greater energy use for growth compared with feeding mash diets (Latshaw and Moritz, 2009). Pelleting broiler diets also reduces feed wastage (Jensen, 2000), which is partially attributed toward preventing sorting larger particles from small particles and minimizing the negative growth performance effects that can occur when not consuming a balanced diet (Falk, 1985). In addition, birds fed pelleted diets spend less time consuming feed, and obtain more energy and nutrients per unit of energy spent during eating, compared with feeding mash diets (Jensen et al., 1962; Jones et al., 1995; Vilarino et al., 1996). In fact, Nir et al. (1994) reported that birds (28 to 40 days of age) were less active and spent one-third of the amount of time consuming pelleted feed compared with broilers fed mash diets. However, research is limited regarding the optimal pellet size and length for achieving the greatest growth performance. Abdollahi and Ravindran (2013) compared feeding pellets that were three, five or seven mm in length to broilers and showed increasing pellet length improved PDI and hardness, but feeding the three mm pellets had resulted in the greatest feed intake with similar weight gain compared with feeding pellets with greater lengths. Finally, pelleting minimizes ingredient segregation (Greenwood and Beyer, 2003) and increases bulk density for more efficient transport and storage, while reducing dust in production feed mills and broiler production facilities (Abdollahi et al., 2013).

Table 2. Summary of feed ingredient characteristics and their impact on pellet quality and pellet mill throughput (adapted from California Pellet Mill Co., 2016)

Ingredient Characteristic	Impact of Pellet Quality	Impact on Pellet Mill Production Rate
Moisture	Increased moisture increases pellet quality	N/A
Protein	High protein contentincreases pellet quality	N/A
Fat	Greater than 2 percent lipid content decreases pellet quality	High lipid content increases production rate
Fiber	High fiber contentmay improve pellet quality	High fiber content decreases production rate
Starch	High starch content reduces pellet quality unless gelatinized with high temperature and moisture during pelleting	N/A
Bulk density	N/A	High density increases production rate
Particle size	Medium or fine particles improve pellet quality	Medium or fine particles increase production rate

Although the temperatures used in conditioning are generally between 80 and 90°C, the need to reduce pathogens such as *salmonella* and *campylobacter* while also achieving desired pellet quality have often led to the use of higher conditioning temperatures (Abdollahi et al., 2013), which can reduce energy and nutrient digestibility (Abdollahi et al., 2011), as well as activity of exogenous enzymes and synthetic vitamins (Abdollahi et al., 2013). Research results on the optimal conditioning temperature on pathogen elimination of feed are somewhat inconsistent, but conditioning temperatures between 80°C (Veldry matteran et al., 1995) and 85°C (Jones and Richardson, 2004) have been reported to be effective for producing salmonella-free feed. McCapes et al., (1989) suggested that 14.5 percent moisture, 85.7°C conditioning temperature, and heating time of 4.1 minutes is necessary for complete inactivation of *salmonella* and *E. coli*. Pelleting feeds involves a combination of shear, heat, residence time and moisture, which may result in partial denaturation of protein in feed (Thomas et al., 1998) that reduces solubility and improves digestibility (Voragen et al., 1995). Unfortunately, if high temperatures are used for processing low-moisture ingredients, Maillard reactions (non-enzymatic browning) can occur, resulting in reduced digestibility of proteins and carbohydrates (Pickford, 1992; Hendriks et al., 1994; Thomas et al., 1998), especially lysine. However, Hussar and Robblee (1962) suggested the typical temperatures used during pelleting are likely to have minimal effects on lysine digestibility.

Pelleting often reduces enzyme activity because exogenous enzymes are susceptible to thermal treatment. Inborr and Bedford (1994) evaluated pelleting broiler feeds at conditioning temperatures of 75, 85 or 95°C for 30 seconds or 15 minutes on β-glucanase activity, starch, total and soluble β-glucans and non-starch polysaccharides and effects on bird performance. Overall, there was a negative quadratic effect of conditioning temperature, and a positive linear effect of enzyme level, on feed conversion and weight gain. Specifically, β-glucanase activity in the pelleted feed was decreased by 66 percent at conditioning temperature of 75°C for when exposed for 30 seconds. These results suggest pelleting causes partial enzyme inactivation, but broiler growth performance was only impacted when the conditioning temperature was greater than 85°C (Inborr and Bedford, 1994).

Pelleting poultry diets containing DDGS

Pelleting of diets containing DDGS can be challenging if the diet contains more than 5 to 7 percent DDGS because adding DDGS increases dietary lipid content, but provides minimal starch, which is necessary for particle binding during the pelleting process (Behnke, 2007). Shim et al. (2011) reported that adding 8 percent DDGS to grower broiler diets and 16 percent DDGS to finisher diets decreased pellet durability. However, in this study, increased amounts of supplemental fat were added to diets as DDGS inclusion rates increased, which likely contributed to decreased pellet durability.

In contrast, several studies have shown pelleting diets containing greater dietary inclusion rates of DDGS can be achieved to support acceptable growth performance of broilers. Wang et al. (2007a,b,c) conducted broiler feeding trials using pelleted diets containing up to 30 percent DDGS. Although pellet durability was not measured in these studies, they reported the pellet quality of the 15 percent DDGS diets was similar to that of the control diets, but a high proportion of fines resulted from pelleting the 30 percent DDGS diets even with the addition of a pellet binder (Wang et al., 2007a,b).

Min et al. (2008) fed pelleted, isocaloric corn-soybean meal-poultry oil-based diets containing 0, 15 and 30 percent DDGS (8.9 percent crude fat) with or without 5 percent glycerin to broilers from 0 to 42 days of age. Starter diets were pelleted with a 2.38 mm die while grower and finisher diets were pelleted using a 4.76 mm die. The percentage of fines increased as DDGS inclusion level increased (**Table 3**). However, despite the increase in fines, body weight of birds fed 15 and 30 percent DDG was improved at 14 days, and there was no effect of dietary DDGS inclusion rate at 28 or 42 days of age. Furthermore, there were no difference in feed conversion for birds fed 0 percent (1.65) and 15 percent (1.64) DDGS, but feeding 30 percent DDGS diets increased feed intake and reduced feed conversion (1.71), which was presumably due to increased fines. Carcass dressing percentage was reduced by feeding the 30 percent DDGS diets, but there was no effect on breast meat yield.

In a subsequent study, Min et al. (2009) showed increasing diet inclusion rate of DDGS up to 25 percent of the diet increased the percentage of fines from 1.49 to 10.81 percent. However, adding lignosulfonate as a pellet binder to the diets was effective in improving pellet quality and reducing the percentage of fines.

The first comprehensive study to evaluate pellet manufacturing efficiency of DDGS diets for poultry was conducted by Loar et al. (2010). Diets containing 0, 15 and 30 percent DDGS, and 30 percent DDGS plus 2 percent sand (particle size 450 μm), along with 1.90 to 3.88 percent poultry fat, were pelleted using a 30.48 cm diameter, 0.476 × 4.496 cm die. Conditioning temperature of the mash was 82°C, and 262 kPa of steam pressure at the globe valve was used. As shown in **Table 4**, the percentage of fines increased and PDI decreased with increasing dietary levels of DDGS, and the addition of 2 percent sand to the 30 percent DDGS diets did not improve these pellet quality measures compared with pelleting the 30 percent DDGS diet without sand. These changes were likely due to reduced starch content of the diets as dietary DDGS inclusion rates increased along with the inclusion of supplemental poultry fat in the mixer prior to pelleting.

Table 3. Effect of dietary inclusion rate of DDGS on pellet quality of broiler diets (adapted from Min et al., 2008)

Feed type	% DDGS	% Fines[1]		
		Mean	SD	CV
Starter[2]	0	1.05	0.67	63.32
	15	4.29	0.30	7.02
	30	12.04	2.40	19.90
Grower[2]	0	10.53	3.02	28.66
	15	18.96	7.94	41.88
	30	26.89	3.38	12.58
Finisher[3]	0	12.83	6.34	49.40
	15	26.60	11.55	43.43
	30	42.64	16.68	39.11

[1]Percentage of pellets that pass through a 2 mm screen.

[2]Pelleted using a 2.38 mm die.

[3]Pelleted using a 4.76 mm die.

Table 4. Effects of dietary DDGS inclusion rate on pellet quality, production rate, and electrical energy use (adapted from Loar et al., 2010)[1]

DDGS %	Fines[2] %	PDI[3] %	Bulk density, kg/m³	Total production rate, MT/hr	Relative electrical energy usage of conditioner, kwh/MT	Relative electrical energy usage of pellet mill, kwh/MT
0	30.8[c]	74.4[a]	631.8[a]	1.211	0.659[bc]	6.531[a]
15	41.7[b]	66.8[b]	622.8[b]	1.266	0.646[c]	5.127[b]
30	54.2[a]	62.1[c]	618.3[b]	1.143	0.749[a]	4.775[c]
30 + sand[4]	54.5[a]	62.3[c]	616.9[b]	1.149	0.723[ab]	5.019[bc]

[a,b,c] Means within a column not sharing a common superscript differ ($P < 0.05$).

[1] Means from four replicate batches.

[2]Percentage of fines present in total pelleted feeds.

[3]Pellet durability index determined by ASAE standard S269.4 (ASAE, 1997).

[4]Sand was added at two percent of the diet in expense of all ingredients.

Salmon (1985) showed that adding increasing concentrations of fat to broiler diets decreased pellet quality. Bulk density also decreased with increasing dietary DDGS levels, which was due to the reduced bulk density of DDGS compared with that of corn, which was partially replaced in these diets. However, the production rate of the pellet mill was similar for manufacturing the 0, 15 and 30 percent DDGS diets. These researchers suggested that the numerical decline in production rate of the 30 percent DDGS diets may be attributed to a reduction in the amount of supplemental inorganic phosphate in these diets, which has a polishing effect inside pellet dies. Adding DDGS to poultry diets reduces the amount of supplemental inorganic phosphorus needed to meet the phosphorus requirement because DDGS contains a significant amount of available phosphorus. Electrical use of the conditioner was greatest for manufacturing the 30 percent DDGS diet, but electrical energy use of the pellet mill declined with increasing level of DDGS in the diet. These differences in energy use may be due to the amount of added fat in these diets because increased pellet mill throughput has been shown to increase with increasing added fat in the diet (Thomas et al., 1998). While it is commonly believed that adding sand can improve various pellet quality and manufacturing efficiencies, it did not affect any manufacturing measurement in this study. Interestingly, when crumbled starter (0 to 14 days of age) diets containing 0 or 8 percent DDGS, and pelleted grower (14 to 28 days of age) diets containing 0, 7.5, 15, 22.5 or 30 percent DDGS were fed, had no effect on growth performance at 14 or 28 days of age. However, when more that 15 percent DDGS was added to grower diets, body weight gain and feed intake was reduced from 14 to 28 days of age.

In a more recent study, Wamsley et al. (2013) showed that increasing dietary DDGS inclusion rates tended not to affect pellet quality until manufacturing the 10 and 20 percent DDGS diets during the finisher phase when production rates increased (**Table 5**). Interestingly, increasing DDGS levels in diets tended to reduce energy consumption by the pellet mill, but it is unclear whether pellet quality, production rate and electrical energy use differences were due to DDGS or supplemental fat inclusion rates.

A few recent studies have evaluated pelleting of reduced-oil (less than 10 percent crude fat) DDGS in broiler diets. Dozier et al. (2015) conducted a study to evaluate growth performance and carcass composition of broilers fed 5, 7, or 9 percent DDGS diets or 8, 10, and 12 percent DDGS diets in starter, grower, and finisher, respectively, using low (5.4 percent crude fat), medium (7.8 percent crude fat), and high (10.5 percent crude fat) DDGS sources. Increasing amounts of poultry fat were added to diets when adding DDGS sources with reduced crude fat content. Samples of pelleted finisher diets were collected to determine PDI using a New Holmen Pellet tester. Although diets containing the three sources of DDGS had variable PDI, the PDI of diets containing 9 percent DDGS were 75.6, 70.8 and 88.3 percent for the low, medium and high oil DDGS diets, respectively. These researchers suggested the greater dietary inclusion rate of poultry fat in the low and medium oil DDGS diets resulted in the numerical reduction in PDI. However, similar to the results reported by Shim et al. (2011), a decrease in PDI with increased diet inclusion rate of DDGS did not adversely affect growth performance.

Kim et al. (2016) conducted a study to determine maximum inclusion rates of reduced-oil DDGS (7.4 percent crude fat) in two finisher diets fed 28 to 42 days of age (finisher 1) and 43 to 56 days of age (finisher 2). Diets contained 0, 8, 16, 18, 24 or 30 percent DDGS in finisher 1 and 0, 8, 16 and 24 percent DDGS in finisher 2. All experimental diets were pelleted using 85°C conditioner temperature and die with dimensions of 0.476 × 3.81 cm. Although pellet quality was not measured in this study, there was no difference in growth performance and carcass characteristics in broilers fed up to 24 percent DDGS in finisher 1 diets (day 28 to 42) and finisher 2 diets (day 43 to 56). These results suggest that although optimum pellet quality may not be achieved, relatively high (24 percent) diet inclusion rates of DDGS can support acceptable growth performance and carcass composition.

Lastly, only one study has evaluated the effects of extrusion of DDGS diets for poultry. Oryschak et al. (2010) formulated diets containing 0, 15 or 30 percent wheat or corn DDGS. Diets were extruded using a twin-screw extruder and increased apparent ileal digestibility (AID) of amino acids in corn DDGS (10 percent) and in wheat DDGS (34 percent). The AID of lysine, threonine, valine and arginine were increased by 31, 26, 23, and 21 percent, respectively from extrusion of diets containing 15 percent corn and wheat DDGS. Furthermore, the AID of gross energy and crude protein was similar between non-extruded corn and wheat DDGS diets, but greater for extruded corn DDGS compared with wheat DDGS diets. These results suggest that improvements in amino acid digestibility can be achieved in corn and wheat DDGS diets using extrusion. Furthermore, extrusion has been shown to be an effective processing method for eliminating microbial contamination (Said, 1996).

Table 5. Effects of dietary DDGS inclusion rate on pellet quality, production rate and electrical energy use (adapted from Wamsley et al., 2013)

Diet	DDGS %	Added fat[1] %	Fines[2] %	PDI[3] %	Total production rate, MT/hr	Relative electrical energy usage of conditioner, kwh/MT	Relative electrical energy usage of pellet mill, kwh/MT
Starter	0	1.25	12.2	86.7	0.712	0.170	6.36
	4	1.38	15.1	85.2	0.824	0.042	5.35
Grower	0	1.45	11.4	78.4	0.819	0.059	5.56
	5	1.63	6.8	78.8	0.816	0.067	5.58
	10	1.81	14.6	81.2	0.789	0.043	4.93
Finisher	0	1.59	6.7	71.1	1.22	0.116	4.94
	10	1.96	11.2	64.3	1.20	0.144	4.87
	20	2.43	10.0	65.8	1.18	0.117	4.12

[1]Total supplemental fat added to the mixer before pelleting.

[2]Percentage of fines present in pelleted feeds collected at the cooler.

[3]Pellet durability index determined by tumbling samples in a Pfost tumbler for 10 min at 50 rpm.

Prediction equations to improve pellet quality of DDGS diets for poultry

The inconsistent results reported in pellet durability, production rates and energy usage among published studies for swine and poultry indicate there are many interactions among the various factors that affect these important measures. To address the complexity of these interactions and predict the effects of adding DDGS to swine and poultry diets, Fahrenholz (2012) developed prediction equations to predict PDI and energy consumption of DDGS diets:

PDI = 53.90 – (0.04 × corn particle size, microns) – (6.98 × percent fat) – (1.12 × percent DDGS) – (1.82 × production rate, kg/hr) + (0.27 × conditioning temperature, °C) + (0.04 × retention time, seconds) + (1.78 × die L:D) + (0.006 × particle size × die L:D) – (0.23 × fat percent × DDGS percent) + (0.06 × fat percent × conditioning temperature) + (0.15 × percent DDGS × die L:D)

This prediction equation had an R^2 = 0.92 and the difference between predicted and actual PDI was 1.1 (about 1 percent variation). Die L:D ratio has the greatest effect on PDI where decreasing die thickness from 8:1 (common in the industry) to 5.6:1 decreased PDI 10.9 units. Increasing conditioning temperature from 65°C to 85°C increased PDI by 7.0 units, and decreasing supplemental soybean oil content in the diet from 3 percent to 1 percent increased PDI by 5.4 units. Decreasing particle size of ground corn from 462 µm to 298 µm contributed to a small, 0.5 unit increase in PDI. Similarly, reducing feed production rate from 1,814 to 1,360 kg/hr increased PDI by only 0.6 units, and had minimal effect on PDI.

kWh/ton= 55.93 – (0.01 × corn particle size, microns) + (1.88 × percentfat) – (0.05 × percent DDGS) – (30.90 × production rate, kg/hr) – (0.41 × conditioning temperature, °C) + (0.17 × retention time, seconds) – (1.20 × die L:D) + (0.02 × corn particle size, microns × production rate, kg/hr) – (0.0001 × corn particle size, microns × conditioning temperature, °C) – (1.41 × percent fat × production rate, kg/hr) – (0.01 × percent fat × percent DDGS) – (0.21 × percent DDGS × production rate, kg/hr) + (0.004 × percent DDGS × conditioning temperature, °C) + (0.22 × production rate, kg/hr × conditioning temperature, °C) – (0.11 × production rate, kg/hr × retention time, seconds) + (1.21 × production rate, seconds × die L:D)

This prediction equation had an R^2 = 0.95 and the difference between predicted and actual kWh/tonwas 0.3 (about 3 percent variation). Increasing conditioning temperature from 65°C to 85°C had the greatest effect on reducing energy consumption (2.7 kWh/ton), while a thinner die L:D (5.6:1) reduced energy use by 1.3 kWh/ton. No other factor (corn particle size – 462 to 298 microns, percent soybean oil = fat – 1 to 3 percent % DDGS – 0 to 10 percent, production rate – 1,360 to 1,814 kg/hr, or retention time – 30 to 60 seconds) affected energy consumption by more than 1.0 kWh/ton. As shown in the equations, there are multiple interactions among factors. Therefore, if current pelleting conditions do not produce desired PDI or energy consumption, modify other factors to achieve better results.

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