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DDGS USER HANDBOOK

4th edition

Precision DDGS Nutrition

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PREFACE AND ACKNOWLEDGEMENTS

The U.S. Grains Council is pleased to publish this 4th edition of the DDGS User Handbook entitled "Precision DDGS Nutrition". The first edition was published in 2007 (10 chapters, 142 pages), the second edition was published in 2009 (16 chapters, 234 pages), and the third edition was published in 2012 (35 chapters, 390 pages). Much has changed over the past 5 years in the production and nutrient composition of U.S. corn DDGS. Most notably, over 90 percent of U.S. ethanol plants are now using technology to partially extract some of the corn oil prior to manufacturing reduced-oil DDGS. This has resulted in a significant change in the nutrient profiles among DDGS sources and created new questions related to energy and nutrient digestibility and feeding value for all animal species. Furthermore, during the past five years, scientists in the U.S. and around the world have conducted innovative research to enhance the nutritional benefits and overcome the limitations of using DDGS in commercial animal feeding programs.

This 4th edition of the U.S. Grains Council DDGS User's Handbook provides a detailed, comprehensive summary with in-depth nutritional insights and new discoveries from over 1,500 published scientific papers since 2010. Animal nutritionists and producers around the world have become increasingly focused on designing precision animal feeding programs that improve caloric and nutritional efficiency to produce high-quality, safe and nutritious food products, while improving environmental sustainability in food animal production systems. Corn DDGS is a unique feed ingredient that is not only an excellent, abundant, and economical source of energy, protein, and phosphorus in diets for all animals, but it also contains many "value-added" properties that provide additional animal health and environmental benefits. This DDGS Handbook is intended to be used by anyone and everyone involved in the production, marketing, purchasing, and use of U.S. corn DDGS and co-products in animal feeds.

The author of this 4th edition, and the three previous editions of the U.S. Grains Council DDGS User Handbook, is Dr. Gerald (Jerry) Shurson, Professor of Animal Nutrition in the Department of Animal Science at the University of Minnesota, St. Paul. Dr. Shurson is a world-renowned, leading expert on the nutritional value and feeding applications of DDGS in animal feeds for all species. He has led an active DDGS research program for 20 years, has collaborated extensively with many other DDGS researchers, and has served as a DDGS technical consultant for the U.S. Grains Council in all export market regions around the world since 1998.

The author is grateful for the contributions and acknowledges Drs. Zhikai Zeng and Jae-Cheol Jang, Post-Doctoral Fellows at the University of Minnesota for conducting meta-analyses of published data related to swine and poultry growth performance studies, and Mr. Steve Markham, Mr. Sean Broderick and Mr. Sam Erwin, CHS, Inc., for their valuable contributions to the chapter on "Factors that Affect DDGS Pricing and Transportation Logistics".

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CHAPTER 1

The Role of U.S. DDGS in Precision Animal Nutrition and Feeding the World Sustainably

WE LIVE IN A WORLD OF TREMENDOUS CHALLENGES. Perhaps one of the greatest of these challenges is to develop and implement new approaches and technologies to provide a growing global population of people with an adequate supply of nutritious, safe, affordable food while preserving natural resources and minimizing negative environmental impacts. The global demand for food is projected to increase by 60 percent by 2050, which will increase demand for meat, milk and eggs from the increasing global middle class of consumers (Alexandratos and Bruinsma, 2012). Fortunately, food animal production is expected to increase and represent 50 percent of global agricultural output value within the next 10 years (FAO, 2008). However, to meet this demand, everyone involved in the food production chain must develop and implement new technologies to increase the amount and efficiency of food produced. Many structural changes and new animal nutritional and production innovations have been developed and are being implemented in food animal production systems around the world. New "precision animal nutrition" innovations are increasing at an accelerating pace to meet the challenges of providing food security, food safety and environmental sustainability. The goal of "precision animal nutrition" is to improve the caloric and nutritional efficiency of converting energy and nutrients present in feed ingredients into high-quality, animal-derived food products.

The global feed industry plays a significant role in feeding the world sustainably. Nearly 1 billion tons of global annual feed production occurs in over 130 countries around the world (IFIF, 2016). While various feed grains such as corn, sorghum, wheat and barley represent major ingredients used in animal feeds, the vast majority of feed ingredients used by the global feed industry are by-products derived from various agricultural and food industries that are unfit for human consumption, but provide valuable energy and essential nutrients in animal feeds. Therefore, the feed industry plays a vital role in "recycling" nutrients, capturing economic value, improving food security and minimizing negative environmental impacts by using these nutrient sources to produce abundant amounts of high quality animal-derived foods.

One of the controversial topics associated with the ability of global agriculture to feed the world sustainably is the "food vs. fuel debate". This controversy involves the tradeoffs of using a portion of the grains and oilseeds produced for biofuels, rather than using this portion for animal feed and human food. However, only 6 percent of total global grain production is used to produce ethanol (Popp et al., 2016), and about 33 percent of the corn used to produce ethanol in the dry-grind ethanol industry is recovered as co-products for use in animal feeds. Therefore, although the demand for corn to produce ethanol has increased, all of the non-starch components are recovered and concentrated (by about three fold) in the co-products compared with concentrations of these nutrients in corn grain, and are being used to displace significant amounts of corn and soybean meal in animal feeds.

The global biofuels industry produces about 52 million tons of co-products for use in animal feed, and about 85 percent of these co-products are produced by the ethanol industry (Popp et al., 2016). The United States ethanol industry is the largest producer of corn co-products, with annual production of about 38 million tons. This amount of corn co-product production is comparable to the amount of soybean meal produced in the U.S. annually, and is being used in large quantities in animal feeds both domestically, as well as in over 30 countries around the world. In addition, DDGS has been the most extensively researched feed ingredient among all major feed ingredients used in the global feed industry in the past 20 years. Research has not only focused on improving caloric and nutritional efficiency, and identifying benefits and limitations for optimal DDGS use in all animal feeds, but research efforts are becoming increasingly focused on characterizing the unique nutraceutical properties and environmental impacts of DDGS.

The high-energy, protein and phosphorus content of DDGS make it a very attractive partial replacement for some of the more expensive traditional energy (corn), protein (soybean meal) and phosphorus (mono- or dicalcium phosphate) ingredients used in animal feeds. When DDGS is added to animal feeds that are properly formulated, it provides excellent animal performance, health and food product quality. These attributes, and others, have made DDGS one of the most popular feed ingredients to use in animal feeds around the world.

Due to the large supply of U.S. DDGS currently being produced, the quantity available for export has continued to increase. Much of this increased demand is a direct result of end-users capturing significant diet cost savings compared to other competing ingredients available. However, even though U.S. DDGS has been used in animal feeds domestically for many decades, it is a relatively unfamiliar feed ingredient for many nutritionists, feed manufacturers and animal producers around the world. As with any new feed ingredient in the global market, there are many technical questions about the nutritional benefits, limitations and use of DDGS in animal feeds to capture the greatest economic value. Even for experienced end-users, the production of reduced-oil (seven to nine percent crude fat) DDGS has led to many questions about energy content and feeding value compared to traditional high-oil (greater than 10 percent crude fat) for various animal species.

This 4th revised edition of the U.S. Grains Council DDGS User Handbook – Precision DDGS Nutrition, was written to provide nutritionists, feed ingredient purchasers, feed manufacturers and animal producers with the most up to date, scientifically based information available related to developing precision nutrition animal feeding programs using DDGS.

The U.S. Grains Council (USGC) provides this comprehensive summary of nutritional information about DDGS to assist current and potential buyers in understanding its nutritional characteristics, recommended maximum dietary inclusion rates, and benefits and limitations for its use in animal feeds. As for any feed ingredient, end-users of DDGS should consult, and seek assistance and advice from a qualified nutritionist when formulating diets and developing feeding recommendations. The USGC has no control over the nutritional content of any specific ingredient selected for feeding. The USGC makes no warranties these recommendations are suitable for any particular herd, flock, or animal. The USGC disclaims any liability for itself or its members for any problems encountered in the use of these recommendations. By reviewing this material, buyers agree to these limitations and waive any claims against USGC for liability arising out of this information.

For more information, contact the U.S. Grains Council at 202-789-0789 or email grains@grains.org. Also visit www.grains.org.

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CHAPTER 2

The “Disconnect” Between DDGS Price and Economic Value

CAPTURING THE GREATEST ECONOMIC VALUE OF DDGS among sources, and using DDGS in precision nutrition feeding programs, requires a new way of thinking about how we determine value. One of the greatest challenges in capturing full economic value of feed ingredients is related to the types of nutritional analysis used to determine purchase price in the global commodity market compared with the actual nutritional measurements used to determine actual economic value in an animal diet. Energy, amino acids and phosphorus are the three most expensive nutritional components in animal diets. In the current feed ingredient commodity market, the purchase price of an ingredient is based on minimum guarantees for crude protein and crude fat. For some ingredients like DDGS, the purchase price is based on the combination of protein and crude fat content of DDGS, often referred to as the “Profat” content. Crude protein, crude fat, along with crude fiber, moisture, ash and nitrogen-free extract, are all components of the proximate analysis that has been used as a routine description of animal feed ingredients since it was first established in 1865 by Henneberg and Stohmann of the Weende Experiment Station in Germany. However, this system of generally characterizing the different chemical characteristics of feed ingredients is grossly inadequate for use in formulating animal diets today because it does not provide accurate information on the amount and proportion of energy used by different animal species, nor does it account for the amount and digestibility of specific nutrients such as amino acids, phosphorus and other essential nutrients required by animals. In fact, studies have shown the crude protein content of corn and DDGS is poorly correlated with lysine content (Cromwell et al., 1999). Furthermore, Fiene et al. showed that while some amino acids (isoleucine, leucine, methionine, threonine and valine) could be predicted with moderate accuracy from prediction equations including crude protein, crude fat and crude fiber, other amino acids (arginine, cystine, lysine and tryptophan) were poorly predicted. Therefore, although analysis of proximate components is relatively simple and inexpensive, animal nutritionists do not use crude protein and crude fat to formulate animal feeds because they are highly inaccurate indicators of usable energy and digestible amino acid content of feed ingredients.

Over the past several decades, major improvements have been made to develop highly accurate nutritional measurements that estimate the actual nutritional value of feed ingredients to animals. Today, animal feeds are formulated on a metabolizable energy (ME) or net energy (NE) basis, and a digestible protein or amino acid basis.

In addition, swine and poultry diets are formulated on a digestible or bioavailable phosphorus basis. Formulation of least-cost or best-cost animal diets is done by using accurate ME or NE, digestible amino acids, and digestible or available phosphorus values for the feed ingredients being fed, and placing constraints on minimum or maximum dietary concentrations of these essential and high-cost nutritional components. Therefore, the analytical methods used to determine price of DDGS are “disconnected” with the measurements used to formulate animal diets and determine economic value. This “disconnect,” frequently results in undervaluing the true economic value of DDGS in animal feeds. Consequently, DDGS is often marketed at a lower price than the actual economic value it provides in complete animal diets.

As shown in Table 1, use of the common method of “Profat” content to assessing nutritional and economic value of DDGS sources would cause most DDGS purchasers to choose DDGS source A as the highest economic value among the five DDGS sources because of its combined high crude protein and crude fat content (37.1 percent). Furthermore, most DDGS purchasers would likely request a price discount for DDGS sources B (31.4 percent Profat) and C (32.4 percent Profat) because of perceived lower nutritional value. However, as shown in Table 2, DDGS source C actually had the greatest economic value ($279/ton) in a growing-finishing swine diet, followed by source A ($266/ton) and B ($252/ton). The DDGS sources E and D had the second (34.4 percent) and third (35.5 percent) highest Profat content, respectively, but these sources had the lowest actual economic value among the five sources. These results provide a "real world" example of why Profat specifications should not be used when making pricing decisions for purchasing DDGS, especially now that accurate ME and SID amino acid prediction equations have been developed for DDGS use in swine and poultry diets (see Chapters 19 and 22).

Although DDGS source C had the second highest NE content, it had the greatest standardized ileal digestible (SID) methionine, threonine and tryptophan content among the five sources, and the combination of these economically important nutritional components resulted in it having the greatest economic value. Furthermore, in this example, there was a $60/ton difference in economic value between the highest- and lowest-value DDGS sources. This difference represents a significant opportunity for DDGS buyers to capture the greatest value by adopting new "state-of-the-art" energy and digestible amino acid prediction equations to determine the true economic value of various DDGS sources. This can be accomplished by requesting laboratory analysis of the DDGS sources being considered for purchasing, working with nutritionists to use prediction equations to estimate the actual ME and SID content for swine and/or poultry, and using current prices of competing ingredients to do "shadow pricing" of DDGS sources.

Another important aspect of this comparison, is that the spot market price for DDGS at the time of conducting this "shadow pricing" comparison was $182/ton. When comparing the actual economic value for each DDGS source with the market price, all of these DDGS sources had between $37 to $92/tongreater economic value than the price that would have been paid to purchase these sources. These results show that DDGS is one of the best values in the global feed ingredient market today. In fact, the "disconnect" between market price and economic value of U.S. DDGS in swine diets can be as much as $100/ton greater actual economic value than the actual purchase price, depending on market price conditions of competing ingredients. In addition, there can also be as much as a $90 difference in economic value per ton between the lowest and highest value U.S. DDGS sources in swine diets. Similar differences also exist when comparing the actual economic value of DDGS in diets for other ruminants, poultry, and aquaculture, with the greatest difference in economic value of DDGS in dairy and beef cattle diets. As a result, these dramatic differences in actual economic value among DDGS sources represent tremendous opportunity to reduce feed cost and improve profitability when using DDGS in animal feeds. However, these value differences can only be captured by using dynamic and accurate ME, NE, digestible protein and amino acids, and digestible phosphorus for the specific DDGS source used in diet formulations for each species.

Table 1. Proximate analysis of 5 commercially available U.S. corn DDGS sources

	A	B	C	D	E
dry matter, %	89.2	89.0	88.9	92.8	88.7
Crude protein, %	29.6	25.7	26.6	27.5	25.7
Crude fat, %	7.5	5.7	5.8	8.0	8.7
Profat, %	37.1	31.4	32.4	35.5	34.4
Crude fiber, %	6.9	6.7	6.7	7.2	7.1
Ash %	4.5	5.2	4.3	4.9	4.8

Source: Dr. Rob Musser, Nutriquest, Mason City, IA.

Table 2. Energy, standardized ileal digestible (SID) amino acid, and available phosphorus content of five commercially available DDGS sources in growing-finishing pig diets[1]

	A	B	C	D	E
ME, kcal/kg	3,237	3,073	3,180	3,182	3,001
NE kcal/kg	2,302	2,190	2,278	2,256	2,141
SID Lysine, %	0.58	0.65	0.63	0.60	0.45
SID Methionine, %	0.48	0.49	0.58	0.46	0.42
SID Threonine, %	0.79	0.80	0.86	0.76	0.62
SID Tryptophan, %	0.16	0.16	0.17	0.16	0.14
Available Phosphorus, %	0.60	0.69	0.65	0.70	0.66
Economic value[2], $/ton	266	252	279	240	219

[1]ME, NE, and SID amino acid content were determined using prediction equations based on chemical composition and were developed specifically for DDGS.

[2]Economic value was determined using "shadow pricing" in least-cost formulation software using the following ingredient prices (DDGS = $182/ton, Corn = $138/ton, Soybean meal - $343/ton)

Source: Dr. Rob Musser, Nutriquest, Mason City, IA.

Conclusions

Although the global commodity feed market continues to use crude protein and crude fat specifications to determine the price of feed ingredients, this system does not adequately capture the actual economic value of DDGS in animal feeds. In fact, because DDGS contains high amounts of a combination of energy, amino acids and phosphorus compared to most other feed ingredients, its economic value is often difficult to accurately determine because its price is determined by price competition in both the corn and soybean meal market. Therefore, it is usually undervalued by $40 to $100/metric ton depending on the species, phase of production, diet inclusion rate, and market conditions. Newly developed energy and digestible amino acid equations can be used to provide accurate values for nutritionists and feed formulators to use when determining "shadow prices" in various diet formulations. Purchasers should use this approach rather than relying on the inaccuracies of crude protein and fat content of DDGS to capture the greatest economic value, manage variability among DDGS sources, and avoid under- and over-feeding energy and nutrients by eliminating the "disconnect" between DDGS price and actual economic value.

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CHAPTER 3

Dry-Grind Production of Ethanol, Distillers Corn Oil and Corn Co-Products

Introduction

THE UNITED STATES IS A GLOBAL LEADER IN BIOFUELS PRODUCTION (ethanol and biodiesel), which is a result of high agricultural productivity and infrastructure, along with government directives to use biofuels for reducing dependence on fossil fuels and greenhouse gas emissions. The U.S. production of ethanol has continued to increase over the past decade, with over 59 billion liters expected to be produced in 2017 (Figure 1; Renewable Fuels Association, 2017) using over 5.5 billion bushels of corn. About 90 percent of U.S. ethanol production occurs in 214 dry grind ethanol plants in 29 states (Figure 2; RFA, 2017). As a result, about 36.5 million metric tons of distillers co-products (Figure 3; RFA, 2017) and 1.5 billion kg of distillers corn oil are expected to be produced in 2017 (Figure 4; RFA, 2017). Today, wet mills comprise only about 10 percent of U.S. ethanol production, and produce a relatively low proportion of corn co-products, with only 3.6 million metric tons of corn gluten feed, and about 705,000 metric tons of corn gluten meal (Figure 5; RFA, 2017). Of the 36.5 million metric tons of distillers co-products produced, about 11 million metric tons are exported (Figure 6; RFA, 2017), with 70 percent used in beef, dairy, swine and poultry feeds in the U.S. (Figure 7; RFA, 2017). Use of DDGS in swine and poultry diets has been increasing since 2004 (Figure 8; RFA, 2017), but beef cattle consume about 45 percent of domestic wet and dry corn co-products, followed by dairy cattle (31 percent), swine (15 percent) and poultry (8 percent).

Beginning in 2005, a few U.S. ethanol plants began extracting some of the corn oil from thin stillage before producing reduced-oil DDGS. The primary incentive for doing this was the relatively low capital investment and cost of operation, which resulted in a rapid return on investment and increased ethanol plant revenue from producing and marketing another co-product. Currently, about 51 percent of distillers corn oil is used in animal feeds (i.e. poultry and swine), 45 percent is used for biodiesel production, and the remaining five percent is used for other industrial purposes (Figure 9; RFA, 2017). As of 2017, exports of distillers corn oil have been minimal, but it is an excellent and economical energy source that should be seriously considered for use as a high-energy feed supplement by feed manufacturers in the export market.

The primary feedstocks used to produce biodiesel around the world are rapeseed, soybean and palm oil (IEA, 2015), but the use of animal fats and recycled cooking oil has been increasing in recent years (Licht, 2013). Soybean oil has been the lowest cost feedstock for biodiesel production in the U.S., but there are incentives to use lower cost alternatives, such as distillers corn oil, to meet future biodiesel production goals at reduced costs, while minimizing competition with edible lipids used for human consumption. The triacylglycerol content of fats and oils can serve as a partial replacement for petroleum in diesel engines once these lipids undergo transesterification, which is a chemical process used to convert fatty acids from glycerol esters to acyl esters (e.g. methyl, ethyl). This conversion is needed because the high viscosities of triacylglycerols result in poor atomization in diesel engine cylinders leading to inefficient combustion, fuel deposition, engine wear, and failure (Ziejewski et al., 1986a,b; Goering et al., 1987).

The purpose of this chapter is to describe the basic principles of ethanol production, corn oil extraction and DDGS production to have a better understanding of the nutritional characteristics and feeding value of the corn co-products produced by the U.S. fuel ethanol industry.

Figure 1. Historic U.S. Fuel Ethanol Production

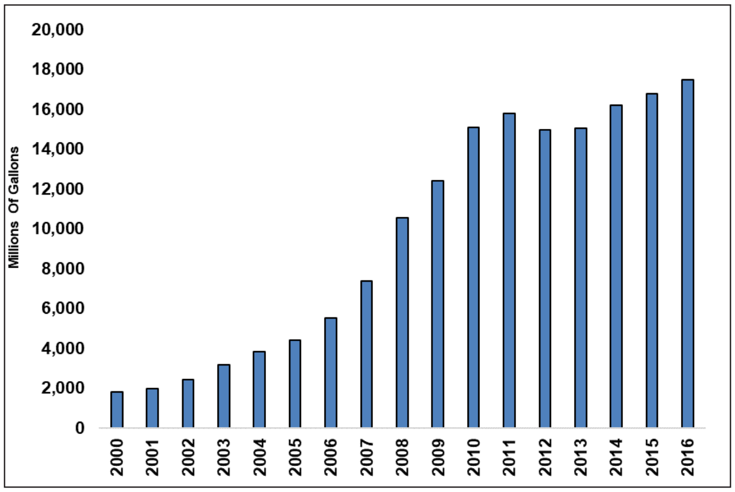


Figure 2. Ethanol Production by Technlogy Types

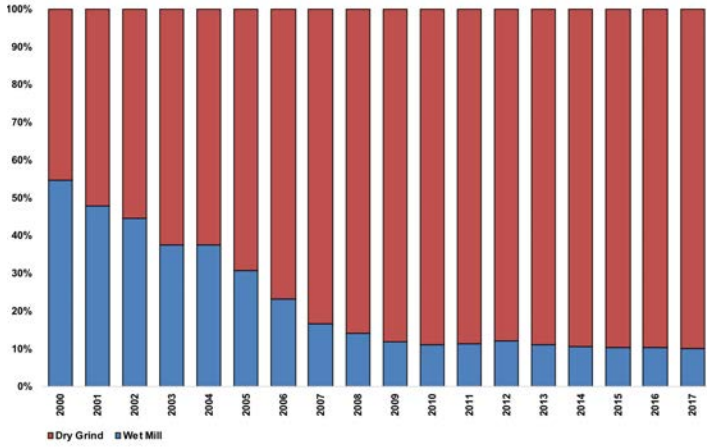


Figure 3. Historic U.S. Distillers Grains Production

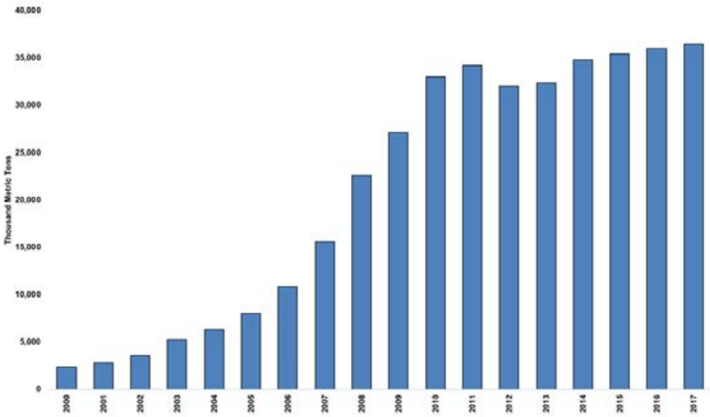


Figure 4. Historic U.S. Corn Distillers Oil Production

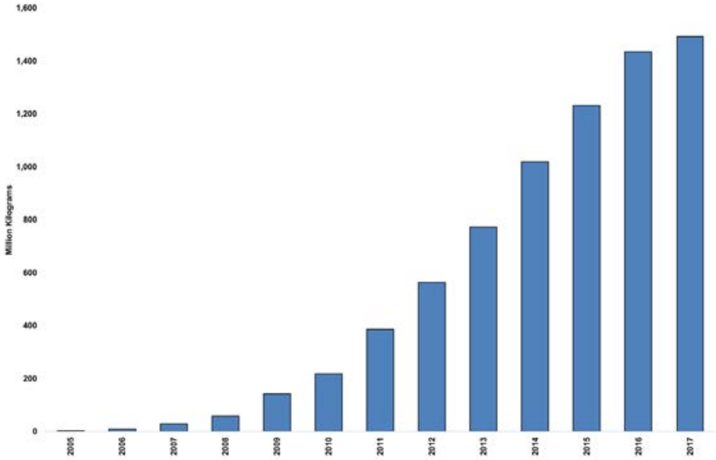


Figure 5. U.S. Fuel Ethanol Co-products Production

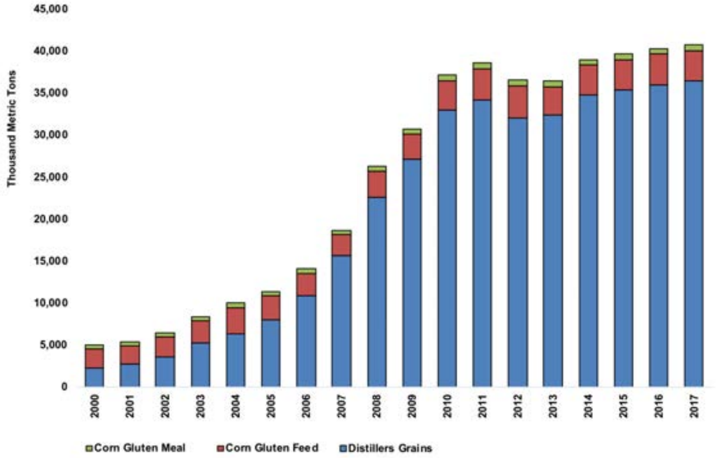


Figure 6. Historic U.S. Distillers Grains Exports

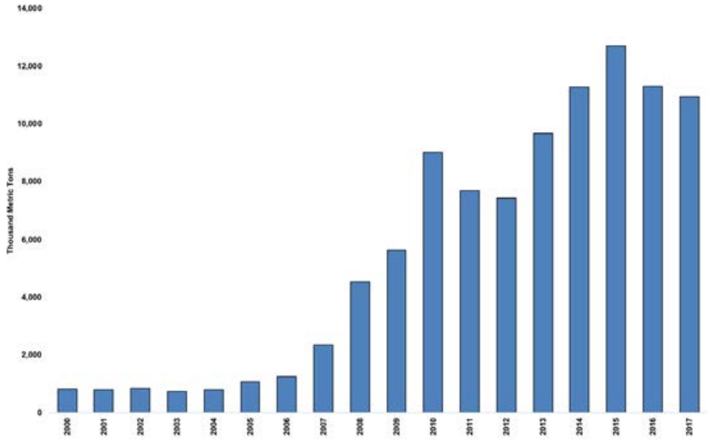


Figure 7. Export and Domestic Use of U.S. Distillers Grains

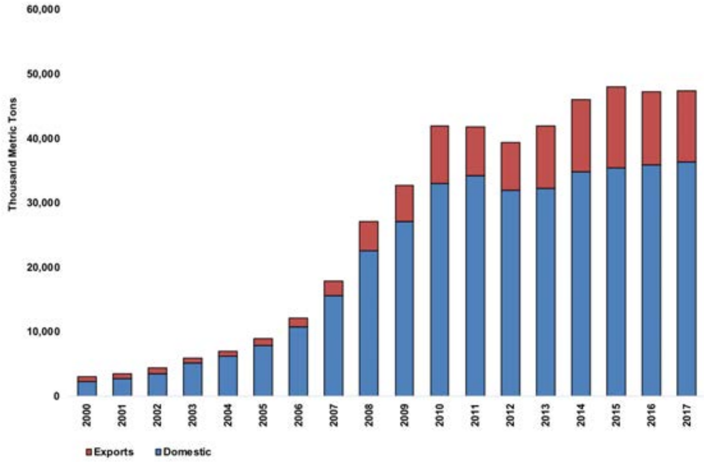


Figure 8. U.S. Distillers Grains Consumption by Species

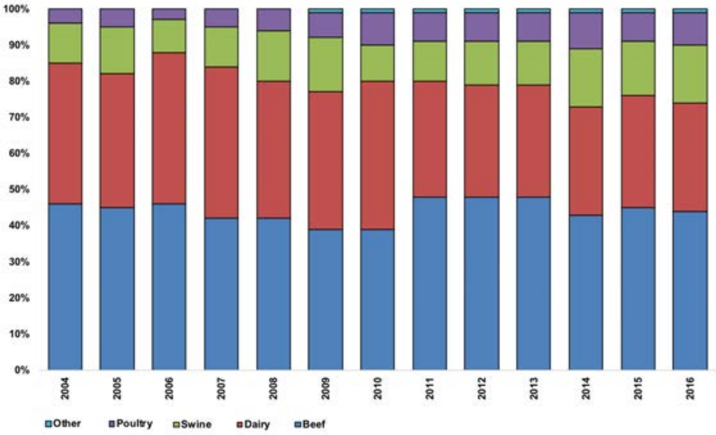
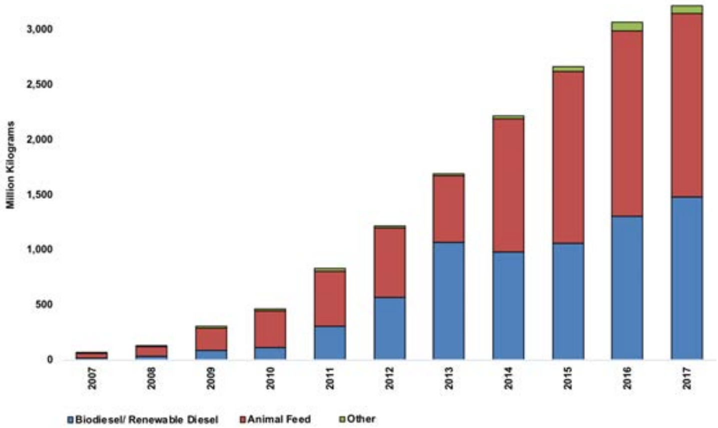


Figure 9. U.S. Corn Distillers Oil Use



Conversion of Starch to Ethanol

In the U.S., corn is the predominant source of starch (glucose) used to produce ethanol. With the exception of Sugarcane, corn provides the greatest ethanol yields compared to any other feedstock being used (Table 1). However, technologies have been recently developed to convert corn fiber and other cellulosic feedstocks to glucose for use in producing ethanol. The energetic efficiency of converting glucose to ethanol is about 51.4 percent, while 48.6 percent is attributed to the production of carbon dioxide. The efficiency of producing ethanol from moisture-free starch is about 56.7 percent. The nutrient composition of the feedstock used to produce ethanol determines the nutrient profile of the distiller's co-products produced.

Table 1. Starch content and ethanoal yield of various feedstocks (adapted from Saskatchewan Agriculture and Food, 1993)

Feedstock	Moisture (%)	Starch (%)	Ethanol Yield (L/MT)
Starch	-	100.0	720
Sugarcane	-	-	654
Barley	9.7	67.1	399
Corn	13.8	71.8	408
Oats	10.9	44.7	262
Wheat	10.9	63.8	375

Dry-grind Ethanol Production

Particle size reduction of grain

As shown in Figure 10, the initial step in ethanol production using dry-grind technology is to reduce the particle size of corn by grinding it with a hammermill. Hammermills crush the corn grain by high-speed, rotating hammer tips. The fineness of the ground corn is determined mainly by the rotor volume, hammer tip speed, number of hammers and the screen opening size (Dupin et al., 1997). The screens used in the hammermill are normally in the range of 3 to 5 mm in diameter. Particle size of the grain can affect ethanol yield (Kelsall and Lyons, 1999), and therefore, ethanol producers tend to use finely ground corn to maximize ethanol yield. As shown in Table 2, an extra 0.20 gallons (0.85 liters) of ethanol can be produced if the corn is ground through a 5 mm screen compared to an 8 mm screen.

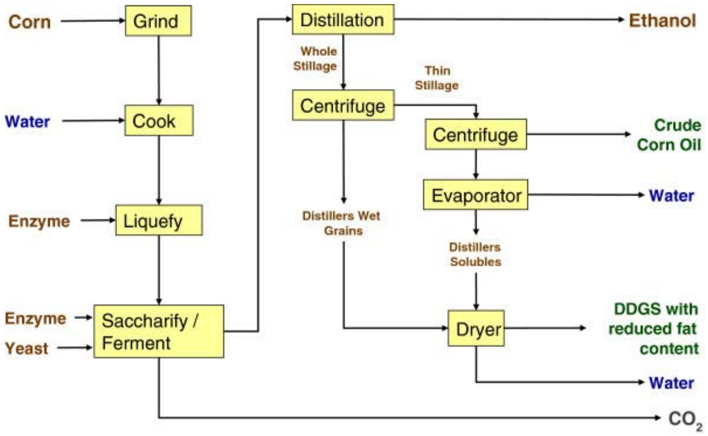


Figure 10. Dry-grind ethanol and co-product production process

Table 2. Ethanol yield from ground corn of different particle size (adapted from Kelsall and Lyons, 1999).

Particle Size	Ethanol Yield (gallons/bushel)
Fine grind corn, 5 mm screen	2.65
Coarse grind corn, 8 mm screen	2.45

Cooking and saccharification

Water and recycled stillage are added to the ground corn, which act as conditioners to begin leaching of soluble protein, sugars and non-starch bound lipids (Chen et al. 1999). Cooking is then used to hydrolyze starch into glucose along with the addition of amylolytic enzymes for yeast (Saccharomyces cerevisiae) to convert glucose to ethanol. Temperatures typically used during the cooking process are 40-60°C in the pre-mixing tank, 90-165°C for cooking, and 60°C for liquefaction (Kelsall and Lyons, 1999). Gelatinization of starch starts to occur between 50 and 70°C. A critical step in converting starch to glucose involves the completeness of starch gelatinization (Lin and Tanaka, 2006). During gelatinization, nearly all of the amylose in the starch granules is leached out (Han and Hamaker, 2001), which increases viscosity due to swollen granules and gels consisting of solubilized amylose (Hermansson and Kidry matteran, 1995).

Complete hydrolysis of the starch polymer requires a combination of enzymes. Amylases are the most widely used, thermostable enzymes in the starch industry (Sarikaya et al., 2000). These include α-amylases or glucoamylase (Poonam and Dalel, 1995). Enzymes must be thermostable for starch hydrolysis to occur immediately after gelatinization. Enzyme use accounts for about 10-20 percent of the ethanol production cost (Gregg et al., 1998).

Some ethanol plants use batch cooking systems whereas others use continuous cooking systems (Kelsall and Lyons, 1999). In a batch cooking system, a known quantity of corn meal is mixed with a known quantity of water and recycled stillage. In the continuous cooking process, corn meal, water and recycled stillage are continuously added into a premix tank. The temperature of the premix tank is maintained just below that needed for gelatinization, and the mash is continuously pumped through a jet cooker. The temperature of the cooker is set at 120°C. From the cooker, the mash passes into the top of a vertical column, and moves down the column in about 20 minutes, it is then passed into a flash chamber for liquefaction at 80-90°C. High temperature-tolerant amylase is added at 0.05-0.08 percent w/w cereal to bring about liquefaction. The retention time in the liquefaction/flash chamber is about 30 minutes. The pH of the system is controlled to be within 6.0-6.5. Batch systems use fewer enzymes compared to continuous systems and are also more energy efficient. The main disadvantage of batch systems is reduced productivity or feedstock utilization per unit of time.

Fermentation

Fermentation is the process where yeast convert sugars to alcohol. The most commonly used yeast is Saccharomyces cerevisiae (Pretorius, 2000) because it can produce ethanol to a concentration as high as 18 percent in the fermentation broth. Saccharomyces is also generally recognized as safe (GRAS) as a food additive for human consumption (Lin and Tanaka, 2006). In ideal fermentation, about 95 percent of sugar is converted to ethanol and carbon dioxide, one percent is converted into cellular matter of the yeast cells, and four percent is converted into other products such as glycerol (Boultonet al., 1996). Yeast use accounts for about 10 percent of the ethanol production cost (Wingren et al., 2003).

Pre-fermentation is used to achieve the desired number of yeast cells for fermentation and is a process that involves agitation for 10-12 hours to achieve 300 to 500 million cells/ml. Fermentation takes place at a temperature of about 33°C (Thomas et al., 1996), at a pH of about 4.0 (Neish and Blackwood, 1951), and lasts between 48-72 hours (Ingledew, 1998). In addition to ethanol, carbon dioxide is produced and can either be collected or is released into the air.

The control of normal yeast growth is a key factor in efficient ethanol production. The activity of the yeast is highly dependent on the temperature of the fermentation system. Torija et al. (2003) reported the optimum temperature for reproduction and fermentation in yeast is 28 and 32°C, respectively. Fermentation efficiency of S. cerevisiae at high temperatures (above 35°C) is low (Banat et al., 1998). Therefore, a cooling mechanism is required in fermentation systems.

One of the challenges of managing fermenters in an ethanol plant is preventing contamination with other microbes. Microbial contamination causes reduced ethanol yield and ethanol plant productivity (Barbour and Priest, 1988). The most common organisms associated with microbial contamination are lactobacilli and wild yeasts. These microbes compete with Saccharomyces cerevisiae for nutrients (trace minerals, vitamins, glucose and free amino nitrogen) and produce inhibitory end-products such as acetic and/or lactic acid. Dekkera/Brettanomyces wild yeasts have become a concern in fuel alcohol production (Abbott and Ingledew, 2005). A reduction in lactic acid bacterial contamination is currently achieved by using antibiotics in fuel ethanol plants (Narendranath and Power, 2005).

Distillation of ethanol

After fermentation, ethanol is collected using distillation columns. Ethanol collected from the fermenters is contaminated with water, and is purified using a molecular sieve system to remove the water and produce pure ethanol.

Corn oil extraction

Although the majority (over 90 percent) of U.S. ethanol plants are using various oil extraction technologies to remove varying amounts of oil before producing DDGS, additional distillers corn oil extraction may occur in the future because the remaining ethanol plants not currently extracting corn oil may adopt this technology, and new technologies have been developed and are being implemented to extract additional oil in ethanol plants currently extracting corn oil. Crude corn oil can be produced at corn ethanol plants by extracting the oil from the thin stillage portion of the DDGS production process (CEPA, 2011). Corn oil extraction from thin stillage occurs after fermentation and distillation, and before the drying to produce DDGS. Corn oil extraction systems have been added to existing ethanol plants to increase the energy efficiency of the plant as well as increase the total amount of fuel produced per metric ton of corn processed. The installation of corn oil extraction equipment in an existing ethanol plant facilitates the production of a biodiesel feedstock without affecting ethanol production volumes.

Different corn oil extraction technologies are available commercially to the ethanol industry. Several commercial proprietary processes are used to extract corn oil from thin stillage after distillation of ethanol. Most of the ethanol industry is using a process where corn oil is extracted from thin stillage after it is removed from the whole stillage using centrifugation (CEPA, 2011). Thin stillage contains approximately 30 percent of the oil available in the corn, and the resulting partially concentrated thin stillage is heated and the corn oil is extracted by a second centrifuge. Heat exchangers use steam to raise the temperature of the thin stillage to facilitate extraction, so that after corn oil is extracted, thermal energy from the stillage is recovered in heat exchangers to heat the incoming stillage. In general, these processes involve using various configurations of decanters, centrifuges, and heat to physically separate 30 to 70 percent of the oil in this co-product stream. All of the distillers corn oil produced through these processes is not suitable for human food use. However, solvent (hexane) extraction is routinely used to extract corn oil from corn germ to produce high quality corn oil for human consumption in wet mills (Moreau, 2005). Hexane extraction is very effective in capturing 90 percent of the corn oil in DDGS, but the high capital investment costs for constructing a hexane extraction facility has limited the adoption of this technology in the ethanol industry. Currently, only one facility (Novita, Brookings, SD) is using hexane extraction to remove corn oil from DDGS. This facility produces feed grade corn oil and a low-oil (3.5 percent crude fat) DDGS.

For every 3.8 liters of ethanol produced, 2.4 kg of DDGS is produced without the use of corn oil extraction (CEPA, 2011). However, with corn oil extraction, DDGS yield is reduced by approximately 0.06 kg per liter of ethanol produced, which represents a 9.4 percent reduction. Removal of corn oil affects the nutritional profile of the DDGS, primarily by reducing the crude fat content, with variable effects on energy and protein content. Refer to Chapters 13, 15, 17, 18, 20, 21, 24, and 25 for more information about the effects of feeding reduced-oil DDGS to various animal species.

Co-product production

The water and solids remaining after distillation of ethanol are called whole stillage. Whole stillage is comprised primarily of water, fiber, protein and oil. This mixture is centrifuged to separate coarse solids from liquid. The liquid, called thin stillage, is subjected to an additional centrifugation step to extract oil before going through an evaporator to remove additional moisture to produce condensed distiller's solubles (syrup), which contains about 30 percent dry matter. Condensed distillers solubles (CDS) can be sold locally to cattle feeders or combined with the coarse solids fraction and dried to produce dried distiller's grains with solubles (DDGS). The coarse solids, also called wet cake, contain about 35 percent dry matter and can be sold to local cattle feeders without drying, dried to produce dried distiller's grains, or mixed with condensed distiller's solubles and dried to produce DDGS (88 percent dry matter). The proportion of various types of co-products produced by dry grind ethanol plants is shown in Figure 11.

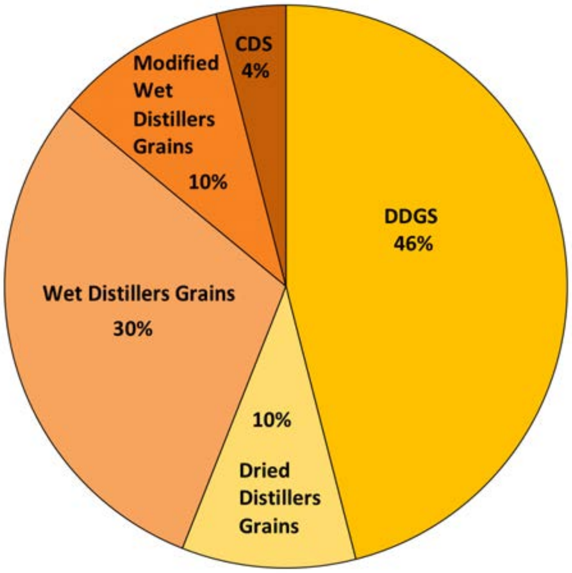


Figure 11. Proportion of various types of co-products produced in dry grind ethanol production (RFA, 2017)

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CHAPTER 4

Chemical Composition and Energy Value of Distillers Corn Oil for Swine and Poultry

Introduction

DISTILLERS CORN OIL (DCO) IS USED AS A HIGH QUALITY ENERGY SOURCE primarily in poultry and swine diets because of its high metabolizable energy (ME) content and relatively low price compared with other feed fats and oils. The market price of DCO is closely related to the price of yellow grease in the U.S. fats and oils market, but DCO has substantially greater ME content than yellow grease, and a comparable ME content to that found in soybean oil. Some market segments of U.S. poultry and pork industries have chosen to produce chicken and pork by feeding only "vegetable-based" diets (which include vegetable oils) to meet specific consumer demands as part of their marketing strategies. Furthermore, the widespread outbreak of Porcine Epidemic Diarrhea virus in the U.S. in 2013 led many veterinarians and nutritionists to remove animal-(porcine) derived feed ingredients from swine diets (e.g. choice white grease, animal by-product protein meals), and use only plant-based ingredients (e.g. corn, soybean meal, distillers dried grains with solubles (DDGS) and distillers corn oil) to reduce the perceived risk of transmission of this virus and other pathogens that may be present in feed ingredients to commercial farms. However, use of distillers corn oil in swine diets has generally been limited to the nursery and early grower phases because feeding high concentrations of corn oil reduces pork fat firmness. A reduction in carcass fat firmness can reduce yields when processing pork bellies into bacon, and reduces pork quality acceptability in the Japanese export market. However, a GRAS-(Generally Recognized As Safe) approved commercial feed additive (Lipinate™, Nutriquest, Mason City, IA) can be used as an effective method of preventing a reduction in pork fat firmness when feeding high dietary inclusion rates of DDGS or DCO in the U.S.

As a result of the large quantities of DCO produced, its high ME content, and competitive price, an official definition for DCO use in animal feeds has been defined and approved by the Association of American Feed Control Officials (2017):

> "33.10 _____ Distillers Oil, Feed Grade, is obtained after the removal of ethyl alcohol by distillation from the yeast fermentation of a grain or a grain mixture and mechanical or solvent extraction of oil by methods employed in the ethanol production industry. It consists predominantly of glyceride esters of fatty acids and contains no additions of free fatty acids or other materials from fats. It must contain, and be guaranteed for, not less than 85 percent total fatty acids, not more than 2.5 percent unsaponifiable matter, and not more than one percent insoluble impurities. Maximum free fatty acids and moisture must be guaranteed. If an antioxidant(s) is used, the common or usual name must be indicated, followed by the words "used as a preservative." If the product bears a name descriptive of its kind of origin, i.e. "corn, sorghum, barley, rye," it must correspond thereto with the predominating grain declared as the first word in the name." Proposed 2015, Adopted 2016 rev. 1)

This definition, officially adopted in 2016, specifies the required guaranteed analysis and also applies to solvent-extracted corn oil, which is a different process than the centrifugation processes used by the majority of U.S. ethanol plants. Although limited quantities of deoiled corn DDGS are being produced, a pending AAFCO definition for this new co-product has been proposed as follows:

> "T27.9 _____Deoiled Corn Distillers Dried Grains with Solubles, Solvent Extracted, is the product resulting from the solvent extraction of oil from corn distillers dried grains with solubles (DDGS) to result in a crude fat content of less than three percent on an as-fed basis. It is intended as a source of protein. The label shall include a guarantee form minimum crude protein and maximum sulfur. The words "solvent extracted" are not required when listing as an ingredient in a manufactured feed." (Proposed 2015)

Chemical Composition of Distillers Corn Oil

One of the distinguishing features of distillers corn oil compared with refined corn oil is that DCO sources have greater free fatty acid content (Table 1), which can range from less than two percent to as much as 18 percent. Previous studies evaluating various feed lipids have shown that increasing free fatty acid content reduces ME content for pigs and poultry, which led to the development of DE (swine) and AME_n (poultry) prediction equations (Wiseman et al., 1998). Corn oil is distinguishable from other lipid sources because of its relatively high polyunsaturated acid (PUFA) content, especially oleic (9c-18:1; 28 to 30 percent of total lipid) and linoleic (18:2n-6; 53 to 55 percent of total lipid) acid content. Vegetable oils have greater PUFA content than animal fats, which results in vegetable oils having greater

ME content (Kerr et al., 2015). As a result, DCO contains one of highest ME concentrations of all feed fats and oils, but it is also more susceptible to peroxidation (Kerr et al., 2015; Shurson et al., 2015; Hanson et al., 2015). Feeding peroxidized lipids to pigs and broilers has been shown to reduce growth rate, feed intake and gain efficiency (Hung et al., 2017), and highly peroxidized corn oil reduces efficiency of energy utilization and antioxidant status in nursery pigs (Hanson et al., 2016). However, the addition of commercially available antioxidants to distillers corn oil are effective in minimizing peroxidation of DCO when stored at high temperature and humidity conditions (Hanson et al., 2015). Although the extent of peroxidation (peroxide value, anisidine value and hexanal) in DCO is somewhat greater than in refined corn oil, it is much less than in the peroxidized corn oil fed in the nursery pig study by Hanson et al. (2016), where reductions in growth performance were observed.

Table 1. Chemical composition and peroxidation measures of refined corn oil and distillers corn oil (DCO) sources (adapted from Kerr et al., 2016)

Measurement	Refined corn oil	DCO (4.9 % FFA[1])	DCO (12.8 % FFA)	DCO (13.9 % FFA)
Moisture, %	0.02	1.40	2.19	1.19
Insolubles, %	0.78	0.40	1.08	0.97
Unsaponifiables, %	0.73	0.11	0.67	0.09
Crude fat %	99.68	99.62	98.96	99.63
Free fatty acids, %	0.04	4.9	12.8	13.9
Fatty acids, % of total fat				
Palmitic (16:0)	11.39	13.20	11.87	13.20
Palmitoleic (9c-16:1)	0.10	0.11	0.11	0.11
Margaric (17:0)	0.07	0.07	0.07	0.07
Stearic (18:0)	1.83	1.97	1.95	1.97
Oleic (9c-18:1)	29.90	28.26	28.92	28.26
Linoleic (18:2n-6)	54.57	53.11	54.91	53.11
Linolenic (18:3n-3)	0.97	1.32	1.23	1.32
Nonadecanoic (19:0)	ND[1]	0.65	0.65	0.65
Arachidic (20:0)	0.40	0.39	0.39	0.39
Gonodic (20:1n-9)	0.25	0.24	0.24	0.24
Behenoic (22:0)	0.13	0.13	0.12	0.13
Lignoceric (24:0)	0.17	0.19	0.18	0.19
Other fatty acids	0.21	0.41	ND	0.41
Peroxidation measure				
Peroxide value, MEq/kg	1.9	2.9	3.3	2.0
Anisidine value[3]	17.6	80.9	70.3	73.3
Hexanal, µg/g	2.3	4.4	3.9	4.9

[1] FFA = free fatty acids

[2] ND = not detected

[3] There are no units for anisidine value

Table 2 shows a comparison of the chemical composition and peroxidation indicators of two DCO sources with other common feed lipids (i.e. choice white grease, palm oil and soybean oil). Choice white grease (rendered pork fat) consists primarily of oleic acid (9c-18:1), palmitic acid (16:0), and stearic acid (18:0), which result in this lipid source being classified as a saturated fat source compared with DCO. In general, saturated animal fats (i.e. choice white grease) have less ME content than more unsaturated vegetable oil sources (i.e. distillers corn oil). Furthermore, choice white grease contains a greater proportion of saturated fatty acids which makes it less susceptible to lipid peroxidation than DCO, but the temperature and heating time used during rendering can result in a similar amount of peroxidation compared with DCO (Table 2). The predominant fatty acids in palm oil are palmitic (16:0) and oleic (9c-18:1) acid, and the linoleic acid content (9.85 percent) is much less than found in DCO (56 percent). As a result, palm oil is much more resistant to peroxidation, as indicated by a high oil stability index (OSI) compared with DCO, choice white grease and soybean oil (Table 2). In contrast, the fatty acid profile of soybean oil is similar to that of DCO, and contains high concentrations of linoleic acid (53 percent) with moderate concentrations of oleic (23 percent) and palmitic (11 percent) acids. However, unlike DCO, soybean oil contains relatively high concentrations of linolenic acid (18:3n-3), which theoretically makes it more susceptible to peroxidation than DCO because linolenic acid contains more double bonds than linoleic acid in its chemical structure. Surprisingly, the soybean oil source shown in Table 2 had a lower aldehyde (products of peroxidation) content, as measured by anisidine value and 2,4 decadienal, compared with DCO, choice white grease and palm oil. Two other distinguishing chemical components in DCO compared with choice white grease, palm oil and soybean oil is its relatively high total tocopherol (626 to 730 mg/kg) and xanthophylls (92 to 175 mg/kg) content (Table 2). Only soybean oil had greater total tocopherol content than DCO, but soybean oil is essentially devoid of xanthophylls. Tocopherols and carotenoids (xanthophylls) are strong antioxidant compounds that appear to be beneficial in preventing greater peroxidation during the thermal exposure that occurs during the co-product production process. Furthermore, the relatively high concentrations of these compounds in corn oil present in DDGS appear to be beneficial in minimizing oxidative stress when feeding highly peroxidized DDGS sources to nursery pigs (Song et al., 2013). The high xanthophylls content of DCO is a "value-added" feature and incentive for its use in broiler and layer diets as a partial replacement for synthetic pigments to achieve desired pigmentation in broiler skin and egg yolks.

Table 2. Chemical composition and peroxidation measures of distillers corn oil (DCO), choice white grease (CWG), palm oil (PO) and soybean oil (SO; adapted from Lindblom et al., 2017)

Measurement	DCO (4.5 % FFA)	DCO (10 % FFA[1])	CWG	PO	SO
Moisture %	0.68	0.54	0.24	0.02	0.02
Insolubles %	0.18	0.04	0.22	0.02	0.02
Unsaponifiables %	1.53	1.86	0.63	0.21	0.33
Crude fat %	98.7	98.2	98.3	98.6	98.5
Free fatty acids %	4.5	10.0	13.4	0.07	0.04
Fatty acids % of total fat					
Capric (10:0)	ND[2]	ND	0.07	ND	ND
Lauric (12:0)	ND	ND	ND	0.22	ND
Myristic (14:0)	ND	ND	1.28	0.99	ND
Pentadecanoic (15:0)	ND	ND	ND	0.04	ND
Palmitic (16:0)	12.86	12.88	23.25	43.41	10.74
Palmitoleic (9c-16:1)	0.10	0.10	2.44	0.15	0.08
Margaric (17:0)	ND	ND	0.33	0.10	0.09
Stearic (18:0)	1.76	1.73	12.54	4.38	4.20
Oleic (9c-18:1)	26.95	26.56	41.38	39.90	23.08
Linoleic (18:2n-6)	55.88	56.50	16.52	9.85	53.19

Table 2. Chemical composition and peroxidation measures of distillers corn oil (DCO), choice white grease (CWG), palm oil (PO) and soybean oil (SO; adapted from Lindblom et al., 2017)

Fatty acids % of total fat	DCO (4.5 % FFA)	DCO (10 % FFA[1])	CWG	PO	SO
Linolenic (18:3n-3)	1.26	1.26	0.55	0.22	7.28
Nonadecanoic (19:0)	0.10	ND	ND	ND	0.31
Arachidic (20:0)	0.39	0.38	0.19	0.37	0.33
Gadoleic (20:1)	0.28	0.25	0.80	0.14	0.20
Eicosadienoic (20:2)	ND	ND	0.74	ND	ND
Homo-y linoleic (20:3)	ND	ND	0.11	ND	ND
Arachidonic (20:4)	ND	ND	0.30	ND	ND
Behenoic (22:0)	0.12	0.14	ND	0.07	0.35
Docosatrinoic (22:3)	ND	ND	0.14	ND	ND
Docosatetraenoic (22:4)	0.12	ND	ND	ND	ND
Docosapentaenoic (22:5)	0.18	0.19	ND	ND	ND
Other fatty acids	ND	ND	ND	0.15	0.16
Free glycerin %	0.85	0.53	0.58	0.74	0.31
Total tocopherols, mg/kg	730	626	253	67	1,083
Alpha	51	62	50	67	77
Beta	15	15	< 10	< 10	< 10
Delta	29	15	< 10	< 10	< 10
Gamma	635	534	203	< 10	817
Xanthophylls, mg/kg	92	175	< 1	< 1	< 1
Peroxidation measure					
Peroxide value, MEq/kg	1.4	0.4	0.4	1.2	1.6
Anisidine value[3]	30.76	21.47	23.26	11.22	5.87
2,4-decadienal, mg/kg	26.4	ND	17.6	ND	6.2
Hexanal, µg/g	ND	ND	14.7	ND	ND
OSI[4] at 110°C, h	5.15	10.75	4.15	30.05	6.35
Oxidized fatty acids %	1.6	0.9	2.2	1.2	1.4
Polar compounds %	9.38	9.55	20.53	7.40	3.46
TBA[3,5] value	0.04	0.03	0.03	0.01	0.06

[1] FFA = free fatty acids

[3] There are no units for anisidine value or TBA value.

[4] OSI = oil stability index

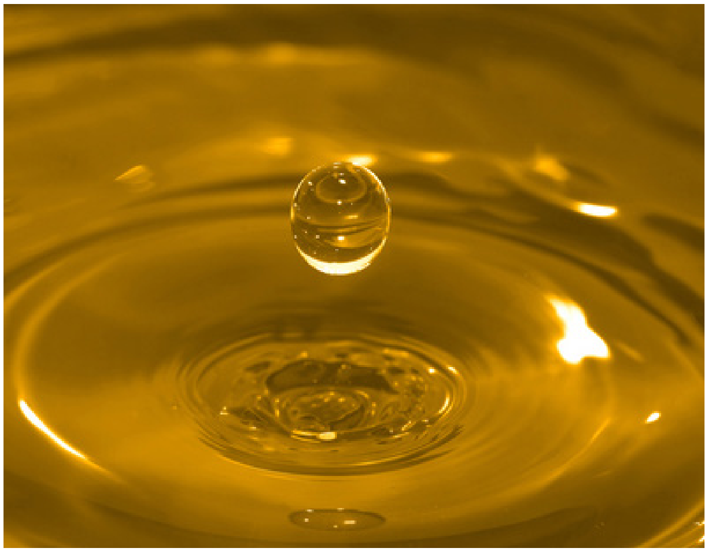
[5] TBA = thiobarbituric acid

Actual and Predicted Digestible and Metabolizable Energy Content of Distillers Corn Oil Sources for Swine

Two studies have been conducted to determine the digestible energy (DE) and ME content of DCO for swine. The first study was conducted by Kerr et al. (2016) to determine the DE and ME content of refined corn oil (0.04 percent FFA), three sources of commercially produced DCO with FFA content ranging from 4.9 to 13.9 percent, and an artificially produced high (93.8 percent) FFA corn oil source, and determine the effect of FFA content on ME content of DCO sources. As shown in Table 3, the ME content of DCO samples ranged from 8,036 to 8,828 kcal/kg, with the 4.9 percent FFA DCO sample containing similar ME content compared with refined corn oil. The ME values for refined corn oil (8,741 kcal/kg), 4.9 percent FFA DCO (8,691 kcal/kg) and 13.9 percent FFA DCO (8,397 kcal/kg) were similar to the value of 8,570 kcal/kg for corn oil reported in NRC (2012). Surprisingly, the 93.8 percent FFA corn oil source had the lowest GE content, but the highest DE and ME content of all corn oil sources. With the exception of the 12.8 percent FFA DCO source having the lowest ME content of all sources, there was no significant detrimental effect of FFA content on DE or ME content of DCO.

In a subsequent study, Lindblom et al. (2017) determined the DE and ME content of two different DCO sources (4.5 and 10 percent FFA), and compared these values with commercially available sources of choice white grease, palm oil and soybean oil (Table 4). The ME values obtained for both DCO samples were substantially less (7,921 and 7,955 kcal/kg) than the values obtained for two of the three DCO sources (8,397 to 8,691 kcal/kg) evaluated by Kerr et al. (2016). It is unclear why there was a difference in ME content of DCO sources between these two studies, but these results provide further support that FFA content of DCO does not appear to affect ME content for swine. It was also surprising the ME content for choice white grease (8,535 kcal/kg) was greater than the ME content of both DCO samples, and was also greater than the NRC (2012) value of 8,124 kcal/kg. It is well documented that unsaturated lipid sources have historically had greater lipid content than saturated fat sources (NRC, 2012). However, it is possible the widespread use of high dietary inclusion rates of DDGS in U.S. growing-finishing pig diets may have resulted in a shift toward more unsaturated fatty acid content in choice white grease obtained from carcasses of these pigs. Evidence for this is supported by the greater linoleic acid content (16 percent) of this source of choice white grease compared with linoleic acid content of (11.6 percent) reported by NRC (2012). Furthermore, there was a slight decrease in palmitic acid (23 percent) in this source of choice white grease compared with 26 percent palmitic acid reported in the NRC (2012). Furthermore, the ME content of the soybean oil source evaluated by Lindblom et al. (2017) was substantially greater (9,408 kcal/kg) than the value of 8,574 kcal/kg reported by NRC (2012). These results show the potential risks of over- or under-estimating ME content of feed fats and oils when using static values from reference databases.

Kerr et al. (2016) evaluated the accuracy of using of prediction equations developed by Wisemann et al. (1998) to predict DE content of DCO sources to determine if these widely used prediction equations are applicable to DCO sources, and provide more dynamic and accurate DE estimates based on variable FFA composition of DCO sources (Table 3). The Wiseman et al. (1998) equations use FFA content, unsaturated to saturated fatty acid ratio, and age of pig as the inputs to estimate DE content. Unfortunately, the results from using these equations showed that DE content was over-estimated in refined corn oil and the 12.8 percent and 13.9 percent FFA DCO sources, provided a similar estimate of DE content for the 4.9 percent FFA DCO source, and greatly underestimated (1,146 kcal/kg) the DE content of the experimentally produced high FFA DCO source. These results suggest that new prediction equations need to be developed specifically for DCO, because the use of the Wiseman et al. (1998) equations does not provide the accuracy and precision necessary to estimate DE content of DCO for swine.



Actual and Predicted Metabolizable Energy Content of Distillers Corn Oil Sources for Broilers

Only one study has been conducted to determine the AME_n content of distillers corn oil for poultry. Kerr et al. (2016) determined the AME_n content of refined corn oil (0.04 percent FFA), along with the same three sources of commercially

Table 3. Actual and predicted DE content and ME content of DCO for nursery pigs (adapted from Kerr et al., 2016)

Measurement	Refined corn oil	DCO (4.9 % FFA[1])	DCO (12.8 % FFA)	DCO (13.9 % FFA)	DCO (93.8 %FFA)
GE, kcal/kg	9,423	9,395	9,263	9,374	9,156
DE, Kcal/kg	8,814^{a}	8,828^{a}	8,036^{b}	8,465^{ab}	8,921^{a}
ME, kcal/kg	8,741^{a}	8,691^{a}	7,976^{b}	8,397^{ab}	8,794^{a}
EE[2] digestibility %	93.2	94.0	91.7	95.0	92.7
UFA:SFA[3]	6.13	5.00	5.61	5.00	4.81
Predicted DE[4], kcal/kg	8,972	8,848	8,794	8,741	7,775
Differencebetweenactualvs. predicted DE, kcal/kg	-158	-20	-758	-276	+ 1,146

[a,b]Means with different superscripts within rows are different (P less than 0.05).

[1] FFA = free fatty acids

[2] EE = ether extract

[3] UFA = unsaturated fatty acids, SFA = saturated fatty acids

[4] Equations based on young pigs (DE) obtained from Wiseman et al. (1998).

Table 4. Energy content and ether extract (EE) digestibility of distillers corn oil (DCO), choice white grease (CWG), palm oil (PO) and soybean oil (SO) in nursery pigs (adapted from Lindblom et al., 2017)

Measurement	DCO (4.5 % FFA)	DCO (10 % FFA[1])	CWG	PO	SO
GE, kcal/kg	9,392	9,395	9,365	9,419	9,419
DE, Kcal/kg	8,001^{b}	8,052^{b}	8,531^{b}	8,293^{b}	9,388^{a}
ME, kcal/kg	7,921^{b}	7,955^{b}	8,535^{b}	8,350^{b}	9,408^{a}
EE[2] digestibility %	84.6^{b}	85.6^{a}	85.5^{a}	84.4^{b}	85.1^{ab}

[a,b]Means with different superscripts within rows are different (P less than 0.05).

[1] FFA = free fatty acids

[2] EE = ether extract

produced DCO used in the pig experiment that ranged in FFA content from 4.9 to 13.9 percent, and an artificially produced high (93.8 percent) FFA corn oil source. As shown in Table 5, the AME_n content was not different among the DCO sources and ranged from 7,694 to 8,036 kcal/kg, and were not different than the AME_n content of refined corn oil (8,072 kcal/kg). However, these values were substantially less than the AME_n values for refined corn oil in (9,639 to 10,811 kcal/kg) reported in NRC (1994). It is interesting that unlike the response in pigs, feeding the 93.8 percent FFA DCO source resulted in a substantial reduction in AME_n content (6,276 kcal/kg) compared with the AME_n content in other corn oil sources. It is unclear why broilers responded differently than pigs when fed this experimentally produced high FFA corn oil source, but these results support previous reports that increased FFA content of feed fats and oils generally reduces AME_n content in broilers.

Similar to the swine comparison, Kerr et al. (2016) evaluated the accuracy of using prediction equations developed by Wisemann et al. (1998) to estimate AME_n content of DCO sources for broilers to determine if these equations can provide accurate and more dynamic AME_n estimates based on variable FFA composition in DCO for broilers (Table 5). The Wiseman et al. (1998) equations use FFA content, unsaturated to saturated fatty acid ratio and age of the bird as the inputs to estimate AME_n content of fats and oils for broilers. Unfortunately, these equations over-estimated AME_n content of all corn oil sources by 379 to 659 kcal/kg. These results suggest that new AME_n prediction equations need to be developed specifically for DCO for broilers because the use of the Wiseman et al. (1998) equations resulted in over-estimating the AME_n content for broilers.

Table 5. Actual and predicted AMEn content of DCO for broilers (adapted from Kerr et al., 2016)

Measurement	Refined corn oil	DCO (4.9 % FFA^1)	DCO (12.8 % FFA)	DCO (13.9 % FFA)	DCO (93.8 % FFA)
GE, kcal/kg	9,423	9,395	9,263	9,374	9,156
AME_n^{2}, kcal/kg	8,072^a	7,936^a	8,036^a	7,694^a	6,276^b
EE^3 digestibility %	91.6^a	89.8^a	89.0^a	88.4a	83.0^b
UFA:SFA^4	6.13	5.00	5.61	5.00	4.81
Predicted AME_n^{5}, kcal/kg	8,680	8,484	8,415	8,329	6,935
Difference between actual vs. predicted AME_n, kcal/kg	- 608	- 548	- 379	- 635	- 659

[1] FFA = free fatty acids

[2] AME_n = nitrogen-corrected apparent ME

[3] EE = ether extract

[4] UFA = unsaturated fatty acids, SFA = saturated fatty acids

[5] Equations based on the average of young and old broilers (apparent ME) obtained from Wiseman et al. (1998) and adjusted to AME_n for broilers based on Lopez and Leeson (2007, 2008) and King et al. (2013).

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CHAPTER 5

Emerging Technologies in Ethanol Production and Nutritional Composition of the High Protein Corn Co-Products Produced

Introduction

THE U.S. ETHANOL INDUSTRY IS CONTINUING TO EVOLVE where dry-grind ethanol plants are becoming biorefineries to not only improve ethanol yield, but also create a more diversified portfolio of corn co-products with potentially higher value for the domestic and international market. Several previous attempts were made to implement front-end fractionation technologies to enhance ethanol yield and create new co-products, but these process technologies were difficult to optimize ethanol and co-production efficiencies and are no longer used. However, beginning in 2005, the predominant new technology is back-end oil extraction from thin stillage, and is being used by the majority of dry-grind ethanol plants today. The processes, chemical composition and energy value of distillers corn oil is discussed in detail in Chapter 4.

Today, much of the focus of new engineering technologies being implemented in some dry-grind ethanol plants involve: 1) corn fiber separation for cellulosic ethanol production, 2) enhanced corn oil extraction methods, and 3) production of high protein (greater than 40 percent) corn co-products.

Brief Description of New ICM, Inc. Process Technologies (www.icminc.com/products)

Four new processes have been developed by ICM, Inc. (Figure 1) that can be added to existing dry-grind ethanol plants to improve ethanol yield, corn oil yield and produce high-protein distillers dried grains (HP-DDG).

Selective Milling Technology™ (SMT)

This process uses newly designed proprietary milling equipment that allows ethanol plants to improve ethanol (up to 3 percent) and corn oil extraction (up to 25 percent) yields, while reducing energy usage (by about 40 percent) and improving operational efficiency of dry grind ethanol plants. The addition of SMT to an existing dry grind ethanol and co-product production process increases the amount of starch available for conversion to ethanol, improves oil recovery and recovers a higher proportion of fiber for other ICM process applications including Fiber Separation Technology™ (FST) and ICM Generation 1.5 processes. Currently, 26 ethanol plants around the world are using the SMT process.

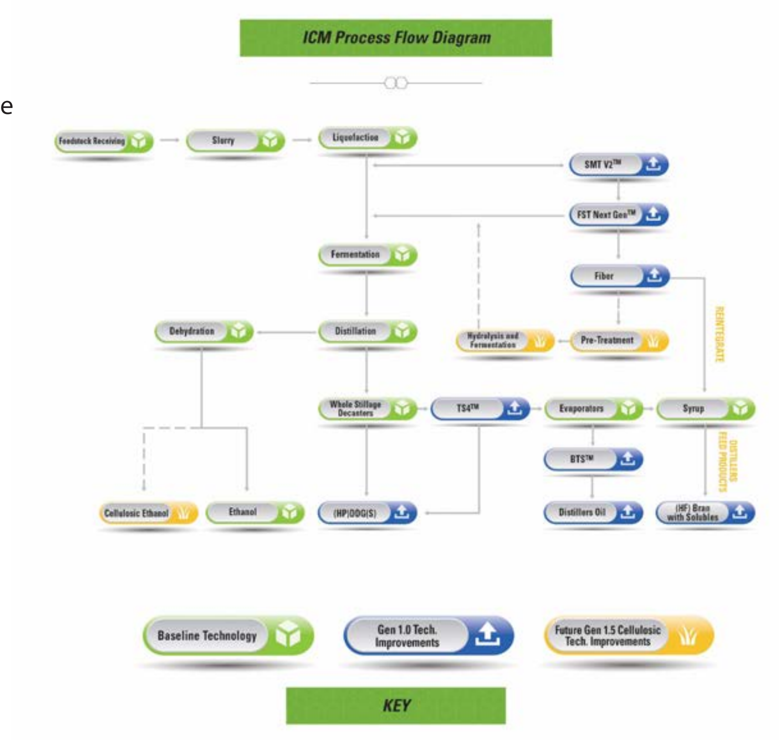

Figure 1. Overview of ICM Selective Milling Technology (SMT), Fiber Separation Technology (FST), Thin Stillage Separation System (TS4) and Grain Fiber to Cellulosic Ethanol Technology (Gen 1.5) in the ethanol and co-product production of dry-grind ethanol plants

Fiber Separation Technology™ (FST)

Fiber Separation Technology™(FST) is follows SMT, and is designed to remove fiber prior to fermentation of corn starch to ethanol. By removing the fiber before fermentation, ethanol plants are able to concentrate the amount of fermentable starch in fermenters and increase the capacity for ethanol production and throughput. As a result, ethanol plants that install FST technology achieve up to 15 percent greater ethanol production capacity, up to 30 percent greater corn oil separation, reduced natural gas use and have the capability of producing high fiber or high protein (40 percent) co-products.

Thin Stillage Separation System™ (TS4)

The ICM TS4 technology has several design configurations that allows separation of the stillage after fermentation into high-value components including protein, solubles and corn oil. This system improves plant operation efficiencies by increasing dryer and evaporator capacity, improving centrifugation and oil separation, increasing throughput, and reducing energy and water consumption of the ethanol plant.

Generation 1.5 – Grain Fiber to Cellulosic Ethanol Technology™ (Gen 1.5)

In addition to using ICM SMT and FST technologies, the implementation of Gen 1.5 allows ethanol plants to produce an additional seven to 10 percent ethanol from corn fiber, and improve oil extraction by up to 20 percent. The system allows ethanol plants to add up to $3 more value per gallon for ethanol produced under current U.S. government cellulosic ethanol incentives. Furthermore, corn fiber is much easier to handle than bulky crop residue, which significantly reduces the capital cost of producing cellulosic ethanol. Use of this process technology results in the production of high protein (40 percent) DDGS.

Brief Description of New Fluid Quip, LLC Process Technologies (http://fqptech.com/proven-technologies)

Three new processes have been developed by Fluid Quip LLC (Figure 2) that can be added to existing dry-grind ethanol plants to improve ethanol yield, corn oil yields, 50 percent purity protein, pure fiber and clean sugars.

Selective Grind Technology (SGT™)

The SGT System is installed in the mash cook process to expose more starch for conversion to ethanol and to shear open the germ to release more corn oil. This process is

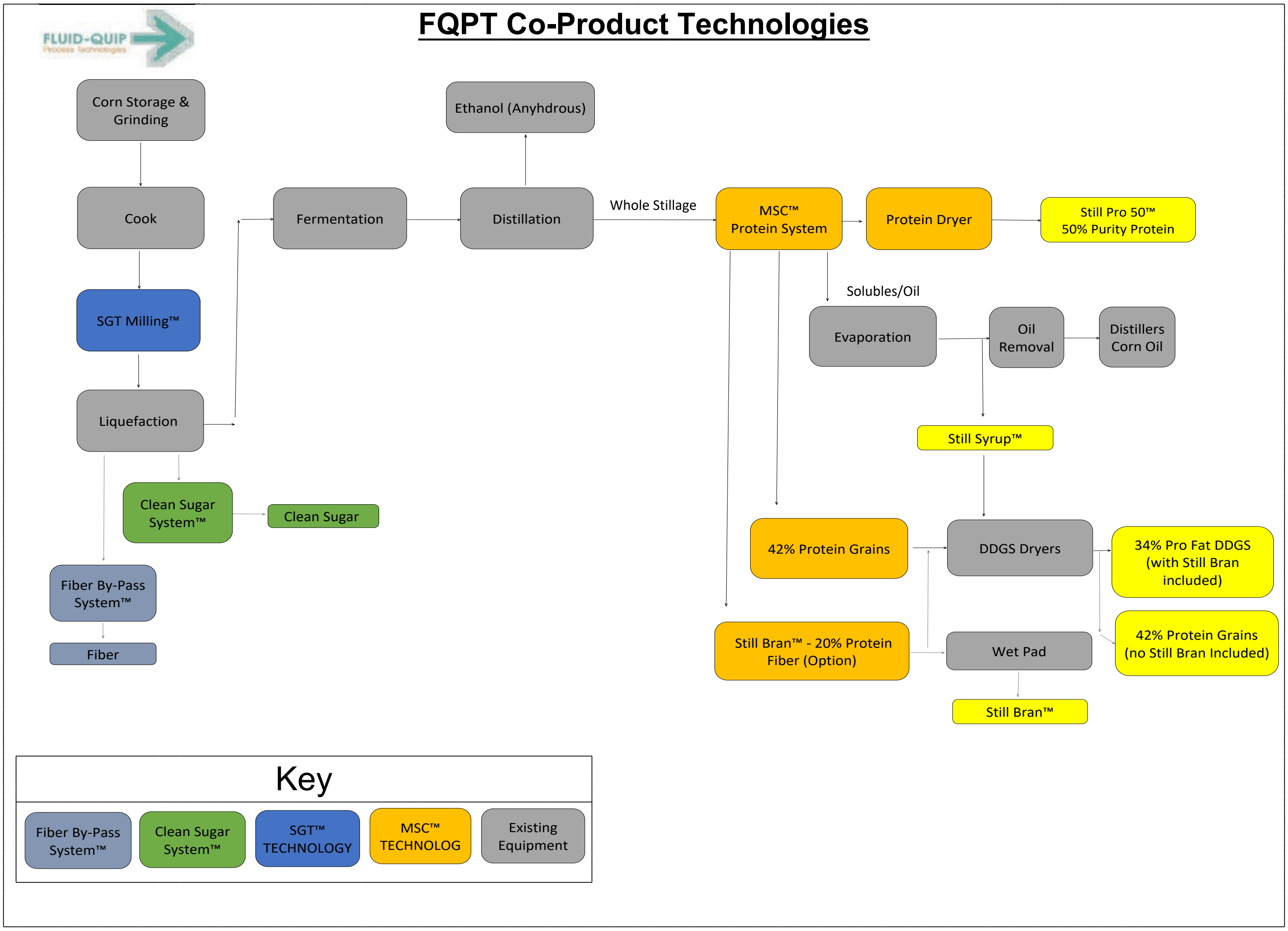

Figure 2. Overview of the process used to separate protein from thin stillage in the production of Still Pro 50™

designed to optimize particle size for maximum ethanol and corn oil yield, resulting in increases in ethanol yield (up to 3.5 percent), increases of corn oil (up to 30 percent) yield.

Maximized Stillage Co-Products™ (MSC)

Fluid Quip's MSC process is designed to separate multiple product streams from whole stillage. MSC produces Still Pro 50™, a 50 percent purity protein product that is a unique blend of spent brewer's yeast and corn gluten meal. Use of this system improves operation efficiencies of dry-grind ethanol plants by removing backset solids and impurities allowing increasing oil yields (up to 30 percent), and ethanol throughput gains (up to 10 percent). The MSC™ protein technology system can be adjusted to produce varying amounts of Still Pro 50™ while meeting typical nutrient specifications in the remaining DDGS for the export market.

Clean Sugar Technology (CST™)

The CST™ System produces an equivalent sugar quality to that of a corn wet mill process. CST™ not only produces an industrial sugar stream, but also yields a high-value corn oil stream and can produce valuable animal feed products including a high-purity protein stream.

Brief Description of Rayeman Compression Dryer System (www.rayemanelements.com)

The Raymen Compression Dryer is unique compared to conventional rotary drum dryers used in the majority of ethanol plants. As the wet DDGS enter the dryer, two patented and specially designed electrically heated screws intermesh with one another to create designated compression points that press water out of the grain. As this occurs, low temperature heat is created due to the shearing and compressing of the grains from the rotating screws, and vaporizes water within the grains at various flash points throughout the process. Use of this process conserves energy used in the co-product drying process, eliminates burning of the co-product, reduces carbon emissions and has a lower capital and operation cost compared with conventional dryers.

Nutrient Composition of New High Protein Corn Co-Products

The most important point to remember when considering purchasing and using any of the new high protein corn co-products is the nutritional composition and energy values are unique and vary among these co-products. Furthermore, these new co-products are being branded with unique names to distinguish each one from the others. Therefore, caution should be used, and generalizations of the protein and nutritional composition should be avoided when comparing the nutritional value of each of these co-products for various animal species.

There are limited nutrient composition data on the new high protein corn co-products being produced, except for Still Pro 50^{TM}, because processes are still being optimized in the ethanol plants using these various new technologies. Therefore, feed ingredient purchasers are encouraged to contact the producers and marketers of these co-products to obtain the most current nutritional information.

As shown in Table 1, the high protein distillers grains (HP-DDG) produced using current ICM technologies contains less crude protein, greater crude fat and phosphorus, and a different amino acid profile than previously produced HP-DDG (NRC, 2012). Studies are underway to determine metabolizable energy (ME) content of ICM HP-DDG in growing pigs and broilers, but based on ME content of previously produced HP-DDG for swine, it is expected the new HP-DDG will contain greater ME content for swine and poultry compared with medium-oil (seven to nine percent crude fat) DDGS. It is important to recognize results from previous studies evaluating the use of HP-DDG in diets for all species may not be applicable to the new ICM HP-DDG because of different nutritional characteristics.

Even less is known about the nutritional composition of FST Fiber+Syrup because it has only been produced in one corn ethanol plant in Brazil for a short time. It is not considered to be a high protein co-product because of its lower crude protein content (25.8 percent), but its nutritional composition is comparable in crude protein, crude fat, NDF and amino acid content to some sources of conventional DDGS. Furthermore, the phosphorus content in FST Fiber+Syrup is the highest (1.34 percent) among all co-products shown in Table 1, which can provide significant cost savings in swine and poultry diets (if it has high digestibility and bioavailability as in DDGS) by reducing the need for inorganic phosphate supplementation in these diets. Studies are underway to determine the ME, standardized ileal digestible amino acids and standardized total tract or bioavailable phosphorus content of this co-product for swine and broilers.

Purestream 40 has less crude protein (42 percent) than HP-DDG and Still Pro 50^{TM}, but has greater lysine, methionine, arginine, leucine and isoleucine content than in HP-DDG. Furthermore, the recently determined ME content (swine) of Purestream 40 is greater than Still Pro 50^{TM}, medium-oil DDGS and soybean meal.

Still Pro 50^{TM} has been the most extensively researched among all of the new corn co-products. This co-product has the greatest crude protein content of all high protein co-products, and is comparable to soybean meal. As a result, the amino acid content of Still Pro 50™ is greater than found in all other high protein co-products, but has less arginine, isoleucine, lysine, phenylalanine and tryptophan than soybean meal. The ME content (swine) of Still Pro 50™ appears to be slightly less than medium-oil DDGS but about 100 kcal/kg greater than soybean meal. The phosphorus content in Still Pro 50™ is comparable to Purestream 40, and greater than DDGS, soybean meal and HP-DDG.

All of these new corn co-products are low in calcium and sodium, but relatively high in phosphorus content compared to other grains and soybean meal. Sulfur content in HP-DDG and Still Pro 50™ is greater than conventional DDGS, and may be a limiting factor for using high (greater than 20 percent) diet inclusion rates of these co-products in ruminant diets.

While all of the new corn co-products can be used as an excellent source of energy, digestible amino acids, and

Table 1. Nutritional composition of new high protein corn co-products (dry matter basis)

dry matter basis	HP-DDG (ICM)[1]	HP-DDG (NRC, 2012)	FST Fiber+Syrup (ICM)[2]	Purestream 40[3]	Still Pro™[4]	Medium-Oil DDGS (NRC, 2012)	Soybean meal (NRC, 2012)
Moisture %	8.8	8.8	10.0	10.7	6.8	10.7	10.0
Crude protein %	44.2	49.7	25.8	42.1	53.4	30.6	53.0
Crude fat %	8.6	3.9	7.8	9.4	5.8	10.0	1.69
NDF %	36.0	36.9	32.9	34.8	39.5	34.1	9.1
ADF %	17.5	22.6	9.3	15.8	20.0	13.5	5.9
ME6, kcal/kg	ND5	4,092	ND	4,275	3,766	3,801	3,660
Arg7 %	1.80 (72-79)	1.78 (85)	1.29	2.10 (87)	2.41 (81)	1.38 (81)	3.83 (94)
Cys %	1.02 (69-74)	0.90 (78)	0.72	0.91 (75)	1.75 (73)	0.49 (73)	0.78 (84)
His %	1.16 (66-72)	1.17 (79)	0.60	1.15 (82)	1.44 (80)	0.83 (78)	1.42 (90)
Ile %	1.52 (68-75)	2.01 (80)	0.57	1.62 (82)	2.12 (75)	1.19 (76)	2.38 (89)
Ile:Lys	1.13	1.50	0.66	1.05	0.98	1.18	0.72
Leu %	4.95 (81-84)	6.78 (86)	1.27	5.14 (89)	6.68(85)	3.64 (84)	4.02 (88)
Leu:Lys	3.69	5.06	1.46	3.36	3.08	3.60	1.22
Lys %	1.34 (47-56)	1.34 (69)	0.87	1.53 (76)	2.17 (61)	1.01 (61)	3.29 (89)
Met %	0.80 (79-83)	1.02 (86)	0.53	0.88 (87)	0.95 (84)	0.64 (82)	0.73 (90)
Phe %	2.29 (77-80)	2.65 (84)	0.63	2.32 (86)	2.67 (81)	1.53 (81)	2.67 (88)
Thr %	1.90 (60-67)	1.74 (75)	0.80	1.66 (75)	2.57 (70)	1.11 (71)	2.07 (85)
Trp %	0.38	0.26 (82)	0.30	0.31 (80)	0.40 (81)	0.22 (71)	0.73 (91)
Val %	2.19 (69-75)	2.32 (78)	0.93	2.15 (81)	2.73 (74)	1.56 (75)	2.48 (87)
Val:Lys	1.63	1.73	1.07	1.40	1.26	1.54	0.75
Ash %	3.0	2.6	7.3	2.8	3.9	4.5	7.0
Ca %	0.01	0.02	0.08	0.03	0.03	0.09	0.37
P %	0.80	0.39	1.34	0.91	1.00	0.67	0.79
S %	0.86	0.82	0.66	0.48	0.51	0.54	0.44
Na %	0.07	0.07	0.54	0.12	0.06	0.34	0.09

[1] Data from HP-DDG sources used in recent swine feeding trials conducted at the University of Minnesota. Values in parentheses are standardized ileal digestibility (swine) determined by Rho et al. (2017).

[2] Data from FS Bioenergia (Brazil)

[3] Data from Purestream 40 used in a recent feeding trial conducted at the University of Minnesota

[4] Data from United Wisconsin Grain Processors, Flint Hills Resources and Fluid Quip, LLC for Still Pro 50™

digestible phosphorus in diets for all animal species, the relatively high leucine, isoleucine and valine content of DDGS and high protein co-products may limit inclusion rates for swine, poultry and fish diets if high amounts of synthetic lysine, threonine and tryptophan are used to reduce the amount of soybean meal used in these diets. Excessive leucine relative to lysine interferes with the utilization of isoleucine and valine and may reduce feed intake and growth rate in pigs. It is unknown if these effects occur in poultry and various species of fish. Research studies are underway to determine if supplementing diets containing high protein corn co-products with synthetic isoleucine and valine are effective when adding these co-products at high (greater than 30 percent) dietary inclusion rates.

Summary of Studies Evaluating Animal Performance When Feeding HP-DDG Produced from Front-end Fractionation

Several studies have been conducted to determine the nutritional value and growth performance of feeding HP-DDG produced from front-end fractionation processes (Table 2). The majority of studies have been conducted for swine and dairy cattle, but only a few studies have been conducted for aquaculture (rainbow trout), broilers and layers and no studies have been published on feeding HP-DDG to beef cattle. The only study relevant to the HP-DDG produced using current ICM processes is by Rho et al. (2017). Because of the differences in energy and nutrient composition of the new ICM HP-DDG compared with previously produced front-end fractionation HP-DDG co-products, caution should be used when evaluating the animal responses from these previously published studies.

Summary of Studies Evaluating Nutritional Value of Still Pro 50™

One of the unique characteristics of Still Pro 50^{TM} is it contains a substantial amount of spent yeast compared with HP-DDG, Purestream 40 and DDGS. Preliminary estimates suggest that Still Pro 50^{TM} contains 29 percent spent yeast compared with 10 percent yeast in DDGS. Therefore, yeast contribute a significant amount of protein and amino acids to this co-product, along with beneficial compounds derived from yeast cell walls (mannans, β-glucans and nucleotides) which have been shown to have beneficial health effects for various food animal species (Shurson, 2017). The mannan content of Still Pro 50^{TM} is about three percent and the β-glucan content is about 8.4 to 8.8 percent (Shurson, 2017). Therefore, in addition to serving as a high quality energy, digestible amino acid and phosphorus source, it may also provide animal health benefits. Preliminary data on amino acid (swine and poultry) and protein (ruminants) digestibility of Still Pro 50^{TM} are shown in Table 3 and 4. See Table 1 for amino acid content and concentrations of other important nutrients in Still Pro 50^{TM}.

Conclusions

Several new high protein co-products are becoming available for domestic and export market use. Preliminary data indicate that although the protein and amino acid content is substantially greater in these co-products compared with conventional DDGS, and the amino acid digestibility and metabolizable energy content varies among co-products. Research needs to be conducted to determine maximum diet inclusion rates and performance benefits of feeding these co-products to swine, poultry, fish and ruminants.

Table 2. Summary of published studies on nutritional value and animal performance from feeding diets containing HP-DDG produced from front-end fractionation processes

Species	Reference
Aquaculture	Overland et al. (2013)
Beef cattle	None
Dairy cattle	Kelzer et al. (2007); Mjoun et al. (2009); Christen et al. (2010); Maxin et al. (2013a, b); Swanepoel et al. (2014)
Broilers	Batal (2007); Kim et al. (2008); Applegate et al. (2009); Rochelle et al. (2011);
Layers	Batal (2007); Kim et al. (2008); Tangendjaja and Wina (2011)
Swine	Widrymatterer et al. (2007); Widrymatterer et al. (2008); Gutierrez et al. (2009a,b); Anderson et al. (2012); Kim et al. (2009); Jacela et al. (2010); Seabolt et al. (2010); a and Ragland (2012); Petersen et al. (2014); Rojo et al. (2016); Rho et al. (2017)

Table 3. Metabolizable energy and amino acid digestibility of Still Pro 50™ for swine and poultry

Nutritional Component	Swine	Poultry
ME, kcal/kg (dry matter basis)	3,766	3,542 (TMEn)
Standardized ileal digestibility (swine) or true ileal digestibility (poultry) of amino acids %		
Arginine	81	94
Histidine	80	90
Isoleucine	75	90
Leucine	85	94
Lysine	61	81
Methionine + cystine	79	88
Phenylalanine	81	92
Threonine	70	87
Tryptophan	81	90
Valine	74	88

[1] Data were obtained from unpublished University of Illinois experiments, sponsored by Fluid Quip and Flint Hills Resources

Table 4. Rumen and intestinal digestibility of protein in Still Pro 50™

Measure	percent as-fed basis
Soluble protein	28.7
Rumen degradable protein	26.1
Rumen undegradable protein	73.9
Intestinal digested protein	63.8
Intestinal digested protein as percent of undegradable protein	86.4
Total tract digested protein	89.9
Intestinal undigested protein	10.1

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CHAPTER 6

Nutrient Composition and Variability of Reduced-Oil Corn DDGS Sources

Introduction

ONE OF THE MOST IMPORTANT FACTORS FOR ACHIEVING PRECISION ANIMAL NUTRITION is to accurately determine the energy, nutrient content and digestibility of the feed ingredients being fed. Accurate nutritional values of feed ingredients minimize the risk of over-feeding or under-feeding energy and nutrients relative to the animal's requirement. Accurate nutritional values are also essential for capturing the greatest economic value of feed ingredients by minimizing "safety margins" frequently assigned to target nutrient allowances when formulating animal diets. Furthermore, if nutritionists have confidence in the energy and digestible nutrient values of the sources of feed ingredients they use to formulate animal diets, they are in a better position to increase usage rates of cost competitive feed ingredients, such as DDGS, to obtain greater diet cost savings.

Variation in nutrient content occurs in all feed ingredients. One of the common complaints among DDGS buyers and nutritionists is the nutrient content is too variable compared with other common feed ingredients. While it is well documented that the energy and nutrient content and digestibility is variable among DDGS sources, especially now that the U.S. ethanol industry is partially extracting oil before manufacturing DDGS, it is no more variable than the nutrient content of other feed ingredients. In fact, in a recent feed ingredient analysis survey conducted by Tahir et al. (2012), the coefficient of variation (CV) for crude protein was less among samples of DDGS (5.4 percent) than among samples of corn (8.7 percent) and wheat (19.1 percent; Table 1). Furthermore, DDGS has the least variability in NDF and phosphorus content compared with corn, soybean meal, wheat and canola meal. However, as expected, the variability in crude fat content among DDGS sources was the greatest among these feed ingredients because the majority of U.S. ethanol plants are partially extracting variable amounts of corn oil prior to manufacturing DDGS. However, this high variability in crude fat content can be partially attributed to the much greater average crude fat content of DDGS (11.6 percent) compared with the crude fat (0.8 to 3.2 percent) content of the other ingredients used in this comparison.

Table 1. Comparison of nutrient content and variability of common ingredients used in poultry diets, and with poultry NRC (1994) values (dry matter basis; adapted from Tahir et al., 2012)

Item	Corn	Soybean Meal	DDGS	Wheat	Canola Meal
No. samples	133	114	89	22	21
Crude protein %	7.8	52.5	29.1	12.7	41.4
CV %	8.7	3.0	5.4	19.1	2.9
percent of NRC	82	97	99	98	101
Crude fat %	2.9	0.8	11.6	1.2	3.2
CV %	23.9	82.1	11.2	55.0	27.6
percent of NRC	69	72	119	43	79
NDF %	11.0	16.8	42.4	13.4	35.8
CV %	18.3	22.9	9.0	16.4	11.0
Phosphorus %	0.32	0.84	0.96	0.42	0.58
CV %	28.7	7.2	6.5	15.0	43.0
percent of NRC	103	121	124	121	80
Phytate phosphorus %	0.19	0.40	0.26	0.25	0.70
CV %	13.4	5.6	27.2	13.9	4.7
percent of NRC	83	162	72	-	74
Ash %	1.2	6.8	4.8	1.8	7.9
CV %	10.9	4.6	13.9	14.9	9.0

Another key point of this comparison by Tahir et al. (2012) is that the nutrient composition of feed ingredients changes over time, and relying on "static" book values from old published databases can lead to significant over- or underestimation of actual nutrient content of commonly used feed ingredients. This is even more critical for DDGS because the nutrient composition continues to change as ethanol plants adopt new processes to improve ethanol yield, extract more corn oil and enhance protein and amino acid content. Therefore, this chapter provides a summary of the most up to date nutrient composition data on DDGS, and is highly recommended nutritionists rely on these data when assessing value and formulating animal diets containing DDGS.

To manage the variation among DDGS sources, some commercial feed manufacturers have identified specific sources that meet their nutritional specifications and quality standards, and work directly with direct marketers that have the capability of providing identity preserved DDGS sources. Some commercial feed companies also use a preferred suppliers list to help minimize variation in DDGS purchases through third party marketers. Perhaps the best approach is to use the recently developed and validated ME and digestible amino acid prediction equations, based on chemical composition of DDGS sources, to accurately estimate the true nutritional value of the source(s) being used (see Chapters 19 and 20 of this handbook for more details of prediction equations for swine and poultry).

Nutrient Content and Variability of U.S. Corn DDGS Sources

Several studies have compiled data sets on the nutrient composition of corn DDGS over various time periods (Olukosi and Adebiyi, 2013; Pedersen et al., 2014; Stein et al., 2016, Zeng et al., 2017). However, caution should be used when identifying databases for use in feed formulation because partial oil extraction in the U.S. ethanol industry began in about 2005, and it is widely used in the U.S. ethanol industry today, which has resulted in a high proportion of DDGS sources containing between five to nine percent crude fat. A reduction in oil content not only increases the variability in crude fat content among DDGS sources, but it also changes the profile of other nutrients. However, although many nutritionists and purchasers of DDGS assume crude protein and amino acid content increases as crude fat content decreases in DDGS, this is not always the case. There is often a disproportionate increase in all other chemical components as the crude fat content of DDGS is reduced. Prior to conducting studies on changes in energy and nutrient content of reduced-oil DDGS, the swine NRC (2012) committee, assumed reduced crude fat content in DDGS would reduce the digestible energy (DE), metabolizable energy (ME) and net energy (NE) content for swine and increase the concentrations of other nutrients. Several subsequent research studies have clearly shown that crude fat content is a poor single predictor of DE, ME and NE content for swine (Kerr et al., 2013: 2015) and poultry (Meloche et al., 2013). For more in-depth information, see Chapters 19 and 20 in the handbook. As a result, NRC (2012) provides estimates of the energy and nutrient profiles of DDGS categorized based on crude fat content. Unfortunately, there were limited data on the ME content and nutrient profiles for medium-oil (n less than 13 for 6 to 9 percent crude fat) and low oil (n less than 2 for less than 4 percent crude fat) DDGS sources. Therefore, these published values do not accurately reflect the variation in nutrient content of the majority of reduced-oil (5 to 9 percent crude fat) DDGS sources currently available from U.S. ethanol plants.

Similar to NRC (2012), a recent review published by Stein et al. (2016) provided nutrient profiles for corn DDGS containing less than 4 percent oil (n less than 3), 5 to 9 percent oil (n less than 15), and greater than 9 percent oil (n less than 100), but this summary is also based on a limited number of samples for DDGS sources containing less than 10 percent crude fat. Because of the poor relationship between crude fat content of DDGS sources and ME content for swine and poultry, prediction equations have been developed and validated (see Chapters 19 and 22). It is highly recommended nutritionists use these ME prediction equations to more accurately determine dynamic estimates of the actual energy content of DDGS sources with variable crude fat content.

Another nutrient composition data set for corn DDGS was published by Olukosi and Adebiyi (2013), which included 44 data sets published between 2004 and 2011, and represented 463 samples of corn DDGS (Table 2). The majority, but not all, of these samples were produced in the U.S., and because most of the samples were obtained between 1997 and 2010, they do not adequately represent the composition of reduced-oil corn DDGS being produced today. However, their analysis is useful in providing estimates of the variability in nutrient composition among DDGS sources over time, as well as for developing prediction equations to estimate the amino acid content from crude protein content in DDGS. Unfortunately, the accuracy of these prediction equations is not adequate for practical use.

Table 2. Variation in chemical composition of corn DDGS sources from 1997 to 2010 (adapted from Olukosi and Adebiyi, 2013)

Analyte	Average	Minimum	Maximum	SD	CV %
Crude protein %	27.9	23.3	34.7	2.4	8.5
Crude fiber %	7.4	6.2	11.3	1.1	15.1
NDF %	36.6	27.7	51.0	5.8	15.7
ADF %	13.6	8.6	18.5	3.3	24.2
Ether extract %	10.8	3.2	17.7	2.4	22.0
Ash %	4.5	3.1	5.9	0.6	13.6
Calcium %	0.04	0.02	0.08	0.02	53.5
Phosphorus %	0.80	0.69	0.98	0.07	8.8

Pedersen et al. (2014) collected and used near infrared reflectance spectroscopy (NIRS) to analyze 72 corn DDGS samples from 21 different ethanol plants in the U.S. The greatest variation (CV %) in composition among sources was for starch (45 percent), total sugars (19 percent), ether extract (crude fat; 17 percent), and acid hydrolyzed ether extract (13 percent), which exceeded the variability in crude protein, NDF, and ADF content (Table 3). These researchers also reported the standard deviation among DDGS sources for each nutritional component which is useful in establishing confidence intervals of expected variation in nutrient profiles.

POET is one of the major ethanol and DDGS producers in the U.S., and owns and operates 27 ethanol plants. Compared with other DDGS sources, POET ethanol plants produce DDGS with the lowest oil content (5.4 percent crude fat) in the market. In a recent survey of the nutrient composition and variability among POET ethanol plants from 2014 to 2016 (Herrick and Breitling, 2016), the nutrient composition of DDGS (dry matter basis) from these plants were: 89.2 ± 1.13 percent dry matter, 30.7 ± 1.57 percent crude protein, 5.36 ± 0.96 percent crude fat, 8.31 ± 0.82 percent crude fiber, 27.8 ± 3.27 percent NDF, 10.6 ± 1.76 percent ADF and 0.92 ± 0.13 percent sulfur.

Factors that Contribute to Nutrient Content Variability of U.S. Corn DDGS Sources

Many factors contribute to the variability in nutrient content of DDGS beyond partial oil extraction. Olentine (1986) listed a number of variables in the raw materials and processing factors that contribute to variation in nutrient composition of distiller's by-products (Table 4). Much of the variation in nutrient content of corn DDGS is likely due to the normal variation among varieties and geographic location where it is grown.

Table 3. Variation in composition of corn DDGS sources based on near infrared reflectance spectroscopy (dry matter basis; adapted from Pedersen et al., 2014)

Analyte	Average	Range	SD	CV %
Moisture %	8.7	6.5 - 12.4	0.8	10
Crude protein %	31.4	27.1 - 36.4	2.1	7
Crude fiber %	7.7	6.4 - 9.5	0.6	7
NDF %	35.1	30.2 - 39.7	2.4	7
ADF %	10.1	8.9 - 11.9	0.6	6
Starch %	6.0	2.9 - 13.9	2.7	45
Total sugars %	9.0	5.4 - 12.6	1.7	19
Ether extract %	9.1	6.5 - 11.8	1.5	17
Acid hydrolyzed ether extract %	11.1	8.4 - 13.5	1.4	13
Ash %	7.1	5.4 - 9.0	0.7	9

Table 4. Factors influencing nutrient composition of distiller's co-products (adapted from Olentine, 1986)

Raw Materials	Processing Factors
Types of grains Grain variety Grain quality Soil conditions Fertilizer Weather Production and harvesting methods Grain formula	Grind Procedure Fineness Duration Cooking Amount of water Amount of pre-malt Temperature and time Continuous or batch fermentation Cooling time Conversion Type, quantity and quality of malt Fungal amylase Time and temperature Dilution of converted grains Volume and gallon per bushel or grain bill Quality and quantity of grain products Fermentation Yeast quality and quantity Temperature Time Cooling Agitation Acidity and production control Distillation Type: vacuum or atmospheric, continuous or batch Direct or indirect heating Change in volume during distillation Processing Type of screen: stationary, rotating, or vibratory Use of centrifuges Type of presses Evaporators Temperature Number Dryers Time Temperature Type Amount of syrup mixed with grain

The composition of corn has changed over time due to genetic improvements in corn varieties, soil fertilization rates and climatic conditions during the growing season. As shown in Table 5, the values for crude fat, crude protein, NDF, ADF, swine DE and poultry TME and AME content in corn are greater than those reported in NRC (2012) for swine and NRC (1994) for poultry (Smith et al., 2015). Therefore, this variability in energy and nutrient composition in corn has direct effects on the nutrient variability among corn DDGS sources. Furthermore, if nutritionists are using energy values for corn from the NRC (1994 and 2012) when formulating poultry and swine diets, they are undervaluing the actual energy content of corn, which has significant economic consequences because energy is the most expensive nutritional component of animal feeds.

The ratio of blending condensed distiller's solubles with the grains fraction to produce DDGS also varies among plants. Because there are substantial differences in nutrient composition between these two fractions, it is understandable the proportion of the grains and solubles blended together will have a significant effect on the final nutrient composition of DDGS. Noll et al. (2006) evaluated the nutrient composition and digestibility of batches of corn DDGS produced with varying levels (0, 30, 60 and 100 percent) of solubles added to the wet grains, which corresponds to adding 0, 12, 25 and 42 gallons of syrup to the grains fraction per minute. Dryer temperatures decreased as the rate of solubles addition to the grains decreased. Particle size increased, and was more variable with increasing additions of solubles to the grains fraction. Adding increasing amounts of solubles resulted in darker colored DDGS (reduced L*) and less yellow color (reduced b*). Increased addition of solubles resulted in increased crude fat, ash, TMEn (poultry), magnesium, sodium, phosphorus, potassium, chloride, and sulfur, but had minimal effects on crude protein and amino acid content and digestibility.

It is also important to remember that nutrient analysis of feed ingredients varies among laboratories, and this has been well documented (Cromwell et al., 1999). As shown in Table 6, a single source of DDGS was collected and sent to four different laboratories for analysis using the same analytical procedures, and results were compared. There were differences in dry matter (92.4 to 96.2 percent), crude fat (9.4 to 13.0 percent) and NDF (26.8 to 40.5 percent) among these four laboratories. All laboratory analysis procedures have inherent analytical variation associated with them that can contribute to differences in results, but other factors such as technician error, sampling error, use of outdated reagents and inadequate calibration and maintenance of analytical equipment can contribute to the discrepancies. To help minimize variation in analytical results for DDGS samples among laboratories refer to Chapter 7 in this handbook for recommended analytical methods for DDGS.

Table 5. Energy and nutrient composition of corn grain sources and comparison with swine NRC (2012) and AME and TME values with poultry NRC (1994; dry matter basis; n = 83 samples; adapted from Smith et al., 2015)

	Swine NRC (2012)	Smith et al. (2015)				
		Average	Range	Difference	SD	CV %
Dry matter %	88.3	86.6	83.7 – 88.9	5.2	1.2	1.4
Crude protein %	9.3	9.5	7.9 – 12.3	4.4	0.98	10.3
Crude fat %	3.9	5.6	3.1 – 10.8	7.7	1.96	35.1
Crude fiber %	2.2	1.7	0.93 – 3.7	2.8	0.42	27.8
NDF %	10.3	10.7	6.7 – 15.4	8.7	2.14	20.0
ADF %	3.3	4.5	1.9 – 8.0	6.1	1.80	39.6
Starch %	70.8	68.5	58.3 – 74.2	15.9	3.4	4.9
Soluble carbohydrates %	-	72.8	63.6 – 79.9	16.3	3.7	5.1
Ash %	1.5	1.4	0.87 – 2.4	1.5	0.28	20.5
GE, kcal/kg	4,454	4,576	4,409 – 4,841	432	101	2.2
DE, kcal/kg (swine)	3,907	4,105	3,904 – 4,344	440	100	2.4
AMEn, kcal/kg	3,764	4,006	3,865 – 4,269	404	94	2.3
TMEn, kcal/kg	3,898	4,086	3,955 – 4,272	317	80	2.0

Table 6. Comparison of nutrient analyses of the same DDGS sample among four laboratories

	Lab 1	Lab 2	Lab 3	Lab 4
Dry matter %	96.2	95.1	92.4	95.1
Crude protein %	29.6	30.3	30.2	29.3
Crude fat %	9.4	13.0	11.1	11.9
NDF %	32.2	26.8	40.5	27.8
Ash %	4.2	5.0	4.4	4.3

Kerr (2013) unpublished data.

Variation in Indispensable Amino Acid Composition of DDGS Sources

As for all other nutritional components, the amino acid content of DDGS can vary substantially among sources. Olukosi and Abebiyi (2013) summarized several amino acid data sets from several studies published between 1997 and 2010, and the average, minimum and maximum concentrations of all of the indispensable amino acids, along with standard deviations and coefficients of variation are shown in Table 7. As previously reported by Fiene et al. (2006), these researchers also showed the correlations between crude protein content and Arg (r = 0.44), Ile (r = 0.26), Lys (r = 0.22), and Trp (r = 0.33) were low and not significant. This means crude protein is a poor indicator of the concentrations of these amino acids in corn DDGS and prediction equations were not developed. Although the concentrations of other indispensable amino acids were significantly correlated with crude protein content (r = 0.68, 0.49, 0.73, 0.81, 0.59 and 0.61 for His, Leu, Met, Phe, Thr, and Val, respectively), they were generally low, and resulting prediction equations had low R^2 values (0.23 to 0.66). These results confirm crude protein content is a poor predictor of amino acid content in corn DDGS, and direct measurement of amino acids is required for accurate determinations.

More recently, Zeng et al. (2017) summarized data sets from 22 peer-reviewed publications and one Master's thesis from studies conducted between 2006 and 2015 (Table 8). These data are more reflective of the chemical composition and variability among current corn DDGS sources than those reported by Olukosi and Adebiyi (2013).

Table 7. Variation in indispensable amino acid composition of corn DDGS sources from 1997 to 2010 (adapted from Olukosi and Adebiyi, 2013)

	Average	Minimum	Maximum	SD	CV %
Arg %	1.22	1.06	1.46	0.098	8.0
Cys %	1.73	1.49	1.97	0.057	11.1
His %	0.74	0.65	0.91	0.070	9.4
Ile %	1.07	0.96	1.25	0.072	6.7
Leu %	3.21	2.89	3.62	0.210	6.6
Lys %	0.90	0.62	1.11	0.118	13.1
Met %	0.52	0.44	0.72	0.063	12.0
Phe %	1.29	1.09	1.51	0.123	9.6
Thr %	1.03	0.93	1.16	0.067	6.5
Trp %	0.22	0.16	0.26	0.022	10.3
Val %	1.42	1.30	1.61	0.095	6.7

Table 8. Variation in chemical composition and amino acid content of corn DDGS sources from 2006 to 2015 (88 percent dry matter basis; adapted from Zeng et al., 2017)

Percent	Average	CV %
Crude protein %	27.1	8.7
Crude fiber %	8.2	26.2
NDF %	34.1	13.4
ADF %	11.5	21.2
Ether extract %	8.8	36.3
Ash %	4.1	24.9
Indispensable amino acids		
Arginine %	1.15	11.8
Histidine %	0.74	14.2
Isoleucine %	0.99	11.8
Leucine %	3.16	13.7
Lysine %	0.80	17.9
Methionine %	0.54	15.1
Phenylalanine %	1.32	12.3
Threonine %	1.01	15.5
Tryptophan %	0.20	16.3
Valine %	1.35	11.1

Non-starch Polysaccharide Composition of DDGS Fiber

Knowledge about the non-starch polysaccharide composition of the fiber fraction in DDGS is important when choosing commercially available enzymes to improve energy and nutrient digestibility in DDGS diets fed to swine, poultry and aquaculture. Pedersen et al. (2014) determined the non-starch polysaccharide (NSP) profile of 47 corn and 11 wheat DDGS samples and showed that NSP's represent about 25 to 34 percent of the composition of corn DDGS samples (Table 9), and most of it is insoluble. This suggests the fiber fraction in corn DDGS has limited digestibility in the small intestine, and limited fermentability in the lower gastrointestinal tracts of swine, poultry and fish. Cellulose represents about 5 to 9 percent of corn DDGS content, and the predominant non-cellulosic polysaccharides are xylose (7.7 percent) and arabinoxylose (12.3 to 17.2 percent), which are also mainly insoluble. The mannose content in corn DDGS (1.7 percent) is substantially greater than found in corn grain, and is likely due to the mannan content in residual yeast cell walls that are present in DDGS. Corn DDGS has greater arabinose (6.2 percent) and uronic acid (1.6 percent) content than wheat DDGS (5.7 and 0.8 percent, respectively), which results in relatively high arabinose to xylose and uronic acid to xylose ratios. This indicates the fiber (heteroxylan) structure is more complex and variable in corn DDGS compared to wheat DDGS, and therefore, is more difficult to degrade with exogenous enzymes. However, the Klason lignin content, which is indigestible, in wheat DDGS was greater than in corn DDGS samples. Klason lignin is not well defined as a chemical constituent, and may contain protein (Maillard products), residual fat and waxes, and cutin in addition to true lignin. These results suggest the concentrations of substituted xylan and souluble NSP's are altered during DDGS production from their original structure in corn grain.

Table 9. Average concentration (%) and variation in the nutrient and non-starch polysaccharide (NSP) composition of 47 corn and 11 wheat DDGS samples (dry matter basis; adapted from Pedersen et al., 2014)

	Corn DDGS				Wheat DDGS			
	Mean	Range	SD	CV %	Mean	Range	SD	CV %
Moisture	8.7	6.5 – 12.4	0.8	10	7.6	6.8 – 8.7	2.0	2
Crude protein	31.4	27.1 – 36.4	2.1	7	33.4	30.3 – 37.9	2.8	9
Ether extract	9.1	6.5 – 11.8	1.5	17	5.2	4.4 – 6.5	0.8	16
Acid hydrolyzed ether extract	11.1	8.4 – 13.5	1.4	13	7.3	6.5 – 8.8	0.8	11
NDF	35.1	30.2 – 39.7	2.4	7	30.6	27.3 – 34.2	2.6	8
ADF	10.1	8.9 – 11.9	0.6	6	10.5	9.5 – 12.2	0.8	7
Crude fiber	7.7	6.4 – 9.5	0.6	7	6.7	5.5 – 8.8	0.9	14
Starch	6.0	2.9 – 13.9	2.7	45	4.0	< 1.0 – 8.8	4.2	103
Total sugars	9.0	5.4 -12.6	1.7	19	9.8	4.6 – 12.4	2.2	23
Ash	7.1	5.4 – 9.0	0.7	9	9.1	8.1 – 10.0	0.4	5
Total NSP	28.3	25.0 - 33.7	2.0	9	26.2	24.2 – 29.1	0.9	4
Soluble NSP	3.1	1.6 - 6.5	0.8	47	6.7	5.3 – 8.0	0.1	2
Cellulose	6.7	5.2 - 9.1	0.8	16	5.0	3.5 – 6.7	1.6	32
Non-cellulosic polysaccharides								
Total xylose	7.7	6.7 - 10.0	0.7	10	8.6	7.0 – 9.3	0.7	8
Soluble xylose	0.6	0.1 - 1.6	0.3	62	2.3	1.5 – 3.2	0.5	22
Total arabinose	6.2	5.6 - 7.2	0.4	7	5.7	5.1 – 6.2	0.0	0
Soluble arabinose	0.7	0.2 - 1.5	0.3	45	1.7	1.2 – 2.2	0.3	15
Total glucose	2.8	2.1 - 4.4	0.4	13	3.3	2.7 – 3.7	0.1	5
Soluble glucose	0.3	0.0 - 1.6	0.4	190	1.1	0.1 – 2.1	1.0	89
Total mannose	1.7	1.2 - 2.0	0.2	12	1.6	1.3 – 1.8	0.2	13
Soluble mannose	0.6	0.4 - 0.9	0.1	19	0.7	0.4 – 0.8	0.1	18
Total galactose	1.5	1.3 - 2.1	0.2	11	1.1	1.0 – 1.2	0.1	11
Soluble galactose	0.3	0.2 - 0.5	0.1	29	0.6	0.4 – 0.7	0.1	18
Total uronic acids	1.6	1.4 - 2.0	0.1	8	0.8	0.7 – 0.9	0.1	12
Soluble uronic acids	0.5	0.3 - 0.6	0.1	11	0.3	0.2 – 0.4	0.0	15
Klason lignin	2.5	1.5 - 4.7	0.7	26	6.6	4.4 – 9.3	2.1	32
Arabinose: Xylose	0.80	0.71 - 0.85	0.0	5	0.66	0.62 – 0.70	0.01	9
Uronic acid: Xylose	0.20	0.16 - 0.23	0.0	8	0.09	0.08 – 0.11	0.0	21

Fatty Acid Composition and Peroxidation Indicators of Corn Oil in DDGS

The fatty acid composition of DDGS is important for several reasons including its contribution to ME and NE values, potential impacts on milk fat concentrations in dairy cattle, effects on pork fat firmness in growing-finishing pigs, and susceptibility to lipid peroxidation during production, transport and storage. As shown in Table 10, the major fatty acids present in DDGS corn oil are linoleic acid (54 percent), oleic acid (26 percent), and palmitic acid (14 percent), of which linoleic and oleic acids are unsaturated fatty acids that contribute to the high energy content of DDGS, but also cause the oil in DDGS to be susceptible to peroxidation. Furthermore, the fatty acid profile does not appreciably differ between high-oil (greater than 10 percent crude fat) and reduced-oil (less than 10 percent crude fat) DDGS sources. Although there is no detectable eicosapentaenoic acid (EPA) concentrations in DDGS oil, there are small amounts of docohexaenoic acid (DHA) present, which is a physiologically important omega-3 fatty acid for neural, retinal and immune functions. There are minimal average differences in the indicators of lipid peroxidation (free fatty acid content, thiobarbituric acid and peroxide value) among high- and reduced oil DDGS sources, but considerable variation in these measures.

For a more comprehensive analysis of lipid peroxidation among DDGS sources, Song and Shurson (2013) analyzed corn oil extracted from 31 corn DDGS sources, and compared these data with a corn grain reference sample (Table 11). The correlations between Minolta L* and b* and peroxide value were - 0.63 and – 0.57, respectively, and greater for TBARS (r = - 0.73 and -0.67, respectively). These significant negative correlations between color measurements and peroxidation measurements of DDGS suggest color may be a useful general indicator of the extent of lipid peroxidation in DDGS sources because brown-colored oxypolymers are produced during the polymerization reactions during lipid peroxidation (Buttkus, 1975; Khayat and Schwall, 1983). However, when Song et al. (2013) fed 30 percent DDGS diets containing the most peroxidized source of DDGS from this study (which also contained

Table 10. Fatty acid composition and extent of lipid peroxidation in DDGS sources with variable crude fat content (adapted from Kerr et al., 2013).

	Average of DDGS sources (>10 % crude fat)	Range	Average of DDGS sources (>10 % crude fat)	Range
No. samples	8		7	
Ether extract %	11.2	10.1 -13.2	8.0	4.9 -10.0
Fatty acid % of total oil				
Myristic, 14:0	0.07	0.06 - 0.08	0.04	ND - 0.08
Palmitic, 16:0	14.2	13.6 - 15.4	14.2	14.0 - 14.6
Palmitoleic, 16:1	0.14	0.12 - 0.16	0.12	ND - 0.15
Stearic, 18:0	2.2	2.0 - 2.6	2.2	2.1 - 2.3
Oleic, 18:1	26.0	24.8 - 27.3	26.2	25.2 - 27.2
Linoleic, 18:2	54.0	51.9 - 55.0	53.9	53.4 - 54.5
Linolenic, 18:3	1.6	1.4 - 1.8	1.6	1.6 - 1.8
Arachidonic, 20:4	ND	ND	ND	ND
Eicosapentaenoic, 20:5	ND	ND	ND	ND
Docosapentaenoic, 22:5	ND	ND	ND	ND
Docosahexaenoic, 22:6	0.18	0.15 - 0.27	0.21	0.16 - 0.26
Lipid peroxidation				
Free fatty acids %	1.7	1.1 - 2.4	1.1	0.6 - 1.7
Thiobarbituricacidabsorbance	7.8	5.7 - 11.8	10.6	5.3 - 17.1
Peroxide value, mEq/kg	5.4	0.2 - 19.0	7.7	0.6 - 17.5

Table 11. Measurements of lipid peroxidation in oil extracted from corn dried distillers grains with solubles (DDGS) and DDGS color (adapted from Song and Shurson, 2013)

		DDGS				
	Corn	Average	Median	Minimum	Maximum	CV %
Peroxide value, mEq/kg oil	3.1	13.9	11.7	4.2	84.1	97.5
TBARS, ng MDA equivalents/mg oil	0.2	1.9	1.7	1.0	5.2	43.6
Color						
L*	83.9	54.1	54.9	45.2	58.1	4.6
a*	2.6	10.9	10.8	9.3	12.4	7.2
b*	20.0	37.3	37.5	26.6	42.7	8.8

0.95 percent sulfur), they observed no negative effects on growth performance of weaned pigs. The lack of a growth performance response was attributed to an increase in sulfur-containing antioxidant compounds resulting from feeding DDGS, and additional supplemental vitamin E was not necessary to prevent a reduction in growth performance. Similar results were also observed by Hanson et al. (2015) when feeding a highly peroxidized DDGS source to weaned pigs. These results suggest that although significant lipid peroxidation occurs in DDGS, it does not appear to negatively affect growth performance and health of weaned pigs. It is possible the relatively high natural antioxidants found in DDGS are sufficient to overcome potential negative effects of feeding peroxidized oil in DDGS to pigs.

Natural Antioxidant and Phytochemical Composition of DDGS

While the primary role of feed ingredients is to provide sufficient amounts of energy and digestible nutrients to meet the requirements of animals, some feed ingredients also contain compounds that provide additional physiological benefits beyond the nutrients they provide to the diet. These compounds are sometimes described as having "functional" or nutraceutical properties (i.e nutritional and pharmaceutical). There are several bioactive compounds in corn that provide health benefits including vitamin E, ferulic acid and carotenoids. These compounds, along with others, may collectively contribute to the antioxidant capacity and potential health benefits of DDGS.

Data on phytochemical content and antioxidant capacity of DDGS are limited. However, quantifying these phytochemical components is important to begin understanding the beneficial effects on gut health and immune system responses observed from feeding DDGS diets to pigs, poultry and fish. Initial evidence suggests DDGS contains significant amounts of various antioxidant compounds that may provide health benefits while preventing oxidative stress from feeding peroxidized oil in some DDGS sources to animals. The first study to quantify various natural antioxidants and phytochemicals in DDGS was conducted by Winkler-Moser and Breyer in 2011. These researchers obtained a sample of DDGS from POET and conducted an extensive analysis to determine the fatty acid profile, tocopherols, tocotrienols, carotenoids, oxidative stability index (OSI) and phytosterols in oil extracted from DDGS (Table 12). Tocopherols are the predominant antioxidants present in oils (Kamal-Eldin, 2006), and are important in minimizing peroxidation under pro-oxidant conditions. Tocotrienols also serve as antioxidants (Schroeder et al., 2006), and appear to contribute to reducing blood cholesterol, preventing cancer and protecting the neural system (Sen et al., 2000). The major carotenoids in corn oil are lutein and zeaxanthin, which have been shown to protect against age-induced macular degeneration and cataracts in humans (Zhao et al., 2006). Beta-carotene and beta-cryptoxanthin are precursors to vitamin A (Bendich and Olson, 1989), and all carotenoids have been shown to have beneficial health effects beyond providing vitamin A activity to diets, including antioxidant activity, improved immune response, and protection against several types of cancer (Bendich and Olson, 1989; Rao and Rao, 2007). Phytosterols are valuable constituents in functional foods because of their ability to reduce blood cholesterol and block cholesterol re-absorption from the lower gastrointestinal tract (Gylling and Miettinen, 2005). Steryl ferulates assist in the cholesterol reducing properties of phytosterols (Rong et al., 1997) and also have antioxidant activity (Nyström et al., 2005). In a more recent study, Shim et al. (personal communication) determined the antioxidant capacity, and tocopherol, tocotrienol, xanthophylls and ferulic acid content and variability among 16 sources of DDGS and compared these values with a corn sample (Table 13). Results from this study showed there is substantial variability in concentrations of these compounds among DDGS sources, but DDGS contains two- to three-fold greater concentrations than found in corn.

Table 12. Fatty acid profile, natural antioxidant compounds, oxidative stability and phytosterols in oil extracted from DDGS (adapted from Winkler-Moser and Breyer, 2011)

Analyte	Concentration
Free fatty acids % oleic acid	10.5 + 0.18
Fatty acids (percent of oil)	
16:0	12.9
16:1	0.1
18:0	1.8
18:1	28.1
18:2	55.5
20:0	0.3
18:3	1.2
20:1	0.0
Calculated iodine value	123.1
Total tocopherols, µg/g	1,104
Alpha-tocopherol, µg/g	296
Gamma-tocopherol, µg/g	761
Delta-tocopherol, µg/g	48
Total tocotrienols, µg/g	1,762
Alpha-tocotrienol, µg/g	472
Gamma-tocotrienol, µg/g	1,210
Delta-tocotrienol, µg/g	80
Total carotenoids, µg/g	75
Lutein, µg/g	47
Zeaxanthin, µg/g	24
Beta-cryptoxanthin	3.3
Beta-carotene, µg/g	0.9
OSI, hours at 110°C	6.62
Total phytosterols, mg/g	21.7
Campesterol, mg/g	2.97
Campestanol, mg/g	1.35
Stigmasterol, mg/g	1.10
Sitosterol, mg/g	10.3
Sitostanol, mg/g	3.72
Avenasterol, mg/g	0.93
Cycloartenol, mg/g	0.71
24-Methylene cycloartanol, mg/g	0.30
Citrostadienol, mg/g	0.31
Steryl ferulates, mg/g	3.42

Table 13. Antioxidant capacity, tocopherols, tocotrienols, xanthophylls and ferulic acid content (dry matter basis) of 16 sources of DDGS compared with corn (adapted from Shurson, 2017)

	Corn	DDGS		
		Average	Minimum	Maximum
Antioxidant capacity, mmol tocopherol equiv./kg	8.1	38.07 + 93.9	29.0	65.2
Tocopherols and tocotrienols, mg/kg				
α-tocopherol	3.2	10.8 + 4.5	4.1	19.7
α-tocotrienol	2.4	9.3 + 2.2	5.4	12.8
γ- tocopherol	32.7	69.0 + 8.6	52.7	81.4
γ-tocotrienol	8.6	14.0 + 2.9	7.6	17.5
δ-tocopherol	10.1	18.2 + 3.6	10.0	24.3
Total tocopherols	57.0	121.3 + 16.9	90.8	141.2
Xanthophylls, µg/kg				
Lutein	385	627 + 218	447	1,343
Zeaxanthin	63	95 + 50	ND	243
Total xanthophylls	448	697 + 257	447	1,586
Ferulic acid, mg/g				
Free ferulic acid	0.01	0.042 + 0.016	0.018	0.087
Total ferulic acid	2.50	7.455 + 0.675	6.774	9.511

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CHAPTER 7

Recommended Laboratory Analytical Procedures for DDGS

Introduction

LABORATORY ANALYSIS OF FEED INGREDIENTS IS A COMMON PRACTICE in the feed industry to verify the ingredient meets guaranteed specifications, determine nutrient composition for use in animal feed formulation, and determine the presence and concentration of potential contaminants. Therefore, the accuracy of measurement of various chemical compounds in feed ingredients including DDGS is essential.

Analytical procedures can be categorized based on the level of validation of a specific laboratory method (Thiex, 2012). A single laboratory validation applies to a specific laboratory, technician, and equipment, whereas, a multi-laboratory validation involves validating a procedure in two to seven laboratories to provide information on how well the results of a method are reproduced outside of the original laboratory. A full harmonized protocol collaborative study validation occurs when at least eight laboratories provide acceptable data using the same procedure. An excellent summary of recommended analytical procedures for DDGS has been published by Thiex (2012) and key points are summarized in this chapter.

Recommended Analytical Methods for Meeting DDGS Trading Standards (AFIA, 2007)

Analyte	Method	Method Description
Moisture	NFTA 2.2.2.5	Lab Dry Matter (105°C/3hr)
Crude protein	AOAC 990.03	Protein (Crude) in Animal Feed
Crude protein	AOAC 2001.11	Protein (Crude) in Animal Feed and Pet Food Copper Catalyst
Crude fat	AOAC 945.16	Oil in Cereal Adjuncts (Petroleum Ether)
Crude fiber	AOAC 978.10	Fiber (Crude) in Animal Feed and Pet Food (F.G. Crucible)

Recommended Methods for Nutrient Analysis of DDGS for Diet Formulation

Analyte	Method	Method Description
Acid detergent fiber (ADF)	AOAC 973.18	Fiber, Acid Detergent and Lignin, H_2SO_4 in Animal Feed and ISO, 2008 are equivalent
Acid detergent lignin (ADL)	AOAC 973.18	Fiber, Acid Detergent and Lignin, H_2SO_4 in Animal Feed and ISO 13906:2008 are equivalent
Amylase-treated neutral detergent fiber (NDF)	AOAC 2002.04	AOAC 2002.04 Amylase Treated Neutral Detergent Fiber in Feeds and ISO 16472:2006 are equivalent
Starch	No official method	AOAC 920.40 is no longer valid because of discontinued production of the enzyme needed for the assay, AOAC 996.11 is most commonly used but has deficiencies.
Amino acids	AOAC 995.12 ISO 13903:2005	AOAC 994.12 for all amino acids except tyrosine and tryptophan
Tryptophan	AOAC 988.15	
Ash	AOAC 942.05 ISO 5984:2002	AOAC 942.05 and ISO 5984:2002 are equivalent. Note: If the ash contains unoxidized carbon, the sample should be re-ashed

Analyte	Method	Method Description
Chlorine	AOAC 969.10 AOAC 943.01 ISO 6495:1999	AOAC 969.10 is the Potentiometric Method and AOAC 943.01 is the Volhard Method
Chromium	No official method	No methods have been validated
Fluorine	Microdiffusion technique (Mineral Tolerances of Animals, 2005)	No methods have been validated
Iodine	ICP-MS technique (Mineral Tolerances of Animals, 2005)	No methods have been validated
Phosphorus	AOAC 965.17 ISO 6491:1998 ISO 27085:2009	AOAC 965.17 Phosphorus in Animal Feed, Photometric Method, ISO 6491:1998 Determination of Total Phosphorus Content – Spectrophotometric Method, and ISO 27085:2009 can be used
Selenium	AOAC 996.16 AOAC 996.17	AOAC 996.16 Selenium in Feeds and Premixes, Fluorometric Method and AOAC 996.17 Selenium in Feeds and Premixes, Continuous Hydride Generation Atomic Absorption Method are acceptable
Sulfur	AOAC 923.01 ISO 27085:2009	AOAC 923.01 Sulfur in Plants and ISO 27085:2009 are comparable
Trace minerals	AOAC 968.08 ISO 6869:2000 ISO 27085:2009	Solubilization involves either dry ash followed by dissolving in acid, or wet ashing various acids depending on the elements being measured. Detection includes gravimetric techniques, visible spectrophotometry, flame and graphite furnace atomic absorption spectrophotometry (AOAC 968.08; ISO 6869:2000), or atomic mass spectroscopic detection (ICP-MS; ISO 27085:2009)

Recommended Procedures for Measuring Possible Contaminants in DDGS (Caupert et al., 2012)

Mycotoxins

Since the 1960s, many analytical methods have been developed for analysis of mycotoxin content in human foods and animal feeds due to the concern of toxicity for human health (Trucksess, 2000). Among them, the methods of thin-layer-chromatography (TLC), enzyme-linked immunosorbent assay (ELISA) and immunosensor-based methods have been widely used for rapid screening, while high-performance liquid chromatography (HPLC) with fluorescence detection (FD) and mass spectrometry detection (MS) have been used as confirmatory and reference methods (Krska et al, 2008). However, due to the need for rapid, accurate, and low cost on-site methods for mycotoxin determinations, test kits have been developed and approved by the Grain Inspection, Packers and Stockyards ADMInistration (GIPSA) of the United States Department of Agriculture, and are specific for use with DDGS (Table 1; http://www.gipsa.usda.gov/GIPSA/webapp?area=home&subject=lr&topic=hb).

These methods are for detection of a single mycotoxin, are relatively simple to use, are quantitatively sensitive and allow high sample throughput. There are six GIPSA approved methods for testing mycotoxins in DDGS (four methods for aflatoxin, one method for fumonisin and one method for zearalenone).

Table 1. GIPSA approved mycotoxin test kits for DDGS (adapted from Zhang et al., 2009)

Brand Name	Manufacturer	Test Range	Test Format	Extraction	Clean-up
Aflatoxin					
Veratox Aflatoxin	Neogen Corporation	5–50 ppb	Microtiter Well Plate Assay	Methanol/water (70 + 30)	ELISA
Ridascreen FAST SC	R-Biopharm	5–100 ppb	Microtiter Well Plate Assay	Methanol/water (70 + 30)	ELISA
Aflatest	Vicam	5–100 ppb	Immunoaffinity Column	Methanol/water (80 + 20)	Affinity column
FluroQuant® Afla IAC	Romer	5–100 ppb	Fluorometry	Methanol/water (80 + 20)	Affinity column
Fumonisin					
AgraQuant Total Fumonisin 0.25/5.0	Romer	0.5–5 ppm	Direct Competitive ELISA	Methanol/water (70 + 30)	ELISA
Zearalenone					
ROSA® Zearalenone	Charm Sciences, Inc.	50–1000 ppb	Lateral Flow Strip	Methanol/water (70 + 30)	

When considering analysis of DDGS samples for possible mycotoxin contamination, it is essential to use approved analytical procedures to get accurate results. High performance liquid chromatography (HPLC) is the preferred method to determine the presence and concentration of mycotoxins in animal feeds. By using HPLC and a variety of detectors, most of the mycotoxins in animal feeds can be separated and detected (Krska et al, 2008). The methods used by major commercial laboratories in the U.S. are listed in Table 2 and have been validated by individual labs and recently published in peer-reviewed scientific journal articles.

Table 2. Recommended methods for mycotoxin analysis in animal feed (adapted from Zhang et al., 2009)

Target	Testing	Detection Range	Reference
Aflatoxin			
Corn, almonds, Brazil nuts, peanuts and pistachio nuts	HPLC – FD	5 – 30 ppb	AOAC 994.08
Deoxynivalenol			
Cereals and cereal products	HPLC – UV	ppm (detection limit)	MacDonald et al., 2005a
Fumonisin			
Corn and corn flakes	HPLC – FD	0.5 – 2 ppm	AOAC 2001.04
Corn and corn-based feedstuffs	Thin layer chromatography (TLC)	ppm (detection limit)	Rottinghaus et al., 1992
T-2			
Food and feed	Thin layer chromatography (TLC)	ppm (detection limit)	Romer Labs, 1986

Table 2. Recommended methods for mycotoxin analysis in animal feed (adapted from Zhang et al., 2009)

Zearalenone			
Corn, wheat and feed	Microtiter Well Plate Assay	0.8 ppm (detection limit)	AOAC 994.01
Barley, maize and wheat flour, polenta and maize-based baby foods	HPLC – FD	0.05 ppm (detection limit)	MacDonald et al., 2005b
Aflatoxins, Deoxynivalenol, Fumonisin, T-2, Zearalenone			
Food and feed	LC/MS/MS	Aflatoxins (1 – 100 ppb); Deoxynivalenol, (1, 1000 ppb) Fumonisin (16 – 3,200 ppb) T-2, (2 – 1,000 ppb) Zearalenone (20 – 1,000 ppb)	Sulyok et al., 2007

Antibiotic residues

The CVM of the U.S. Food and Drug ADMInistration has used a liquid chromatography and ion trap tandem mass spectrometry procedure (Heller, 2009) to determine to presence and concentrations of residues from 13 antibiotics in DDGS including:

- Ampicillin
- Bacitracin A
- Chloramphenicol
- Chlortetracycline
- Clarithromycin
- Erythromycin
- Monensin
- Oxytetracycline
- Penicillin G
- Streptomycin
- Tylosin
- Virginiamycin M1

Extraction efficiency of this procedure ranged from 65 percent to 97 percent with quantitation limits from 0.1 to 1.0 µg/g. Accuracy ranged from 88 to 111 percent with coefficients of variation from 4 to 30 percent. The only FDA approved method for detecting virginamycin residues is a bioassay procedure Phibro (QA@Phibro.com), and is recommended for accurate determination of the presence of virginiamycin residues. The Phibro bioassay accounts for possible biological activity which can only occur with the presence of both subunits of the virginiamycin molecule, compared with the LC-MS method of Heller (2009) which only detects one subunit and can lead to a high percentage of false positive readings.

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CHAPTER 8

Comparison of Nutrition and Quality Differences Between China vs. U.S. DDGS Sources

Introduction

IN RECENT YEARS, CHINA HAS BEEN THE LARGEST IMPORTER OF U.S. DDGS. Fabiosa et al. (2009) reported Chinese feed mills realized a 6 percent reduction in feed costs by using imported U.S. corn DDGS as a partial substitute for soybean meal and corn and other more expensive ingredients. No data are available on the total amount of Chinese DDGS produced annually, but the total DDGS production from five officially designated Chinese plants was 1.69 million MT in 2010 (Jewison and Gale, 2012). Using 2011 data from the China Ministry of Agriculture Feed Industry Office, Jewison and Gale (2012) indicated swine consumed the majority (37 percent) of DDGS, followed by layers (29 percent), broilers (19 percent) and aquaculture (9 percent), whereas ruminants and other consumption represented only four and two percent, respectively.

In 2014 to 2015, China was the world's largest importer of soybeans, rapeseed, DDGS, sorghum, barley and fish meal for use in animal feeds (Gale, 2015). In addition, China is the world's largest food animal producer and manufacturer of animal feed (Gale, 2015). As the human population continues to increase in China, and the consumption of animal derived food products continues to increase, the demand for many imported ingredients, such as DDGS, will continue to increase. However, Jewison and Gale (2012) indicated the demand for U.S. DDGS in China in the future will depend on several factors including the price of corn, soybeans and soybean meal; Chinese government policy, including the recent reforms to the corn support price and official reserve systems; and the price and availability of other substitute feed ingredients. In addition, China's demand for domestic and imported feed ingredients to support its expanding livestock and poultry industries is expected to continue to increase significantly.

Approximately, 66 percent of total U.S. DDGS production is consumed by U.S. beef (45 percent), dairy (31 percent), swine (15 percent), poultry (8 percent) and other (1 percent). Future U.S. DDGS consumption will depend on the price and availability of competing or substitute ingredients such as corn and soybean meal. When the price differential is in favor of DDGS, more of it will be used to replace corn and/or soybean meal in animal feeds. During the last 12 months (July, 2015 to June, 2016) the U.S. spot price for DDGS has ranged from 86 to 115 percent the price of corn, 37 to 50 percent the price of soybean meal, and the cost per unit of protein has been consistently less for DDGS compared to soybean meal (difference ranged from about $0.37 to $2.54 per unit of protein). This protein price advantage for DDGS has made it more competitive as a partial protein substitute in animal feeds compared with soybean meal in the U.S. feed market.

Very little growth in ethanol and DDGS production is expected in the U.S. over the next several years, unless government policy changes are implemented to increase ethanol production. However, this is not expected to occur. Most of the changes that have and will occur in the U.S. ethanol industry are those to create more value from the production of more diversified of co-products. Minor capital expenditures have been made to extract distillers corn oil in the majority (85+ percent) of U.S. ethanol plants. Other minor to modest capital expenditures will be made by some ethanol plants to implement other new ethanol and co-product production technologies. These technologies will result in the production of low-oil (less than 6 percent) DDGS, distillers corn oil, corn fiber for producing cellulosic ethanol, production of high protein DDG or high fiber DDGS, along with a few other specialty co-products.

Differences in DDGS Production Processes

There is very limited published information about Chinese beverage, fuel ethanol and DDGS production processes. However, it is well established that energy and nutrient composition and digestibility of DDGS are affected by several factors including type of grain used, nutrient composition of these feedstocks, as well as various beverage and fuel ethanol and co-product processing methods (Ingledew et al., 2009).

Differences in feedstocks

The feedstocks used to produce ethanol and DDGS are different between U.S. and Chinese ethanol plants, but no data are available on the total amount, type and proportion of feedstocks used to produce Chinese DDGS. Jewison and Gale (2012) said there were five officially designated Chinese ethanol plants in 2010, which used corn, wheat and cassava as feedstocks to produce 1.69 million metric tons of DDGS (4.5 percent of total U.S. corn DDGS production). The beverage alcohol industry in China increased rapidly in the 2000's, but feedstocks used to produce ethanol in China vary by geographical region and include corn, rice, wheat, sorghum, potatoes and cassava (Gale et al., 2009).

Beverage alcohol production often involves using blends of grains, whereas fuel ethanol production in the U.S. involves primarily using corn as a sole feedstock. A few U.S. ethanol plants use sorghum or corn-sorghum blends as feedstocks, but the DDGS produced from these plants is marketed and consumed domestically. Furthermore, only about one to two percent of total DDGS production in the U.S. is derived from beverage alcohol plants, which is presumed to be much less than in China. It appears most of the corn-based fuel ethanol and co-product production in China occurs in the northeast region where the majority of corn is produced. However, although there are no data on the quantities of co-products produced from various types of beverage and fuel ethanol plants in China, it appears corn co-products are the most abundant.

Differences in production processes and nutrient content of DDGS

Fuel ethanol plants in the U.S. use more advanced production technology to produce ethanol and DDGS than those used in China. Most of U.S. ethanol plants were built after 2004 and much of the equipment installed in these plants consists of stainless steel. Ease of cleaning and maintaining high sanitation in ethanol plants is critical for preventing bacterial infections during ethanol fermentation. In contrast, Chinese ethanol plants using corn as a feedstock were built using carbon steel that corrodes easily, allowing bacterial infections to frequently occur during fermentation, which can cause incomplete fermentation, reduced ethanol yields and suboptimal quality of DDGS. Furthermore, corrosion of carbon steel in Chinese ethanol plants has led to extremely high iron content (500 to 1,700 ppm) in DDGS, compared to iron concentrations in U.S. DDGS (120 to 150 ppm). While this may be of minor concern relative to DDGS feeding value, it likely contributes to the darker color of Chinese DDGS.

The majority (over 90 percent) of U.S. ethanol plants are partially extracting oil prior to manufacturing DDGS. Although one of the major ethanol companies (n = 27 ethanol plants) produces DDGS containing 4.5 to 5.0 percent crude fat (as-fed basis), the majority of the U.S. ethanol industry produces DDGS containing a minimum of seven percent crude fat to as much as 14 percent crude fat on an as-fed basis. In contrast, Li et al. (2015) reported that among 25 samples collected from Chinese beverage and fuel ethanol plants, about 44 percent of these samples contained less than six percent crude fat on an as-fed basis. In another recent study, (Jie et al., 2013), obtained 28 corn DDGS sources from several ethanol plants in 11 provinces in China and two corn DDGS samples produced in the U.S. that were imported into China. The range in crude fat content (as-fed basis) was from 1.43 to 15.1 percent, with 32 percent of these samples containing less than six percent crude fat. In contrast, the two U.S. DDGS samples analyzed in this study contained 12.1 and 13.6 percent crude fat. Kerr et al. (2013) evaluated the energy value and chemical composition of 15 corn DDGS sources produced in the U.S. Oil content ranged from 4.3 to 11.2 percent (as-fed basis), but only two samples (13 percent) contained less than six percent crude fat. In summary, it appears that one of several major distinguishing differences between Chinese and U.S. DDGS is that there is a greater proportion of low-oil (less than 6 percent crude fat) DDGS being produced in China than in the U.S.

A recent study published by Li et al. (2015) evaluated the energy value and chemical composition of 25 DDGS samples collected from 17 Chinese beverage (18 samples) and fuel (seven samples) ethanol plants. Therefore, based on the high proportion of DDGS samples collected from the beverage ethanol industry, this is further evidence one of the distinguishing differences between Chinese and U.S. DDGS is that the majority of Chinese corn DDGS is produced by the beverage alcohol industry. Li et al. (2015) classified Chinese DDGS samples into five categories of based on crude fat composition (dry matter basis) and types of processing used:

1. High-oil (9.6 to 13.9 percent crude fat) DDGS (13 samples)

2. Added hull high-oil (8.7 and 9.9 percent crude fat; two samples)

3. Partially reduced-oil (6.6 percent crude fat; one sample) DDGS

4. Reduced-oil DDGS with part of the germ removed (5.1 percent crude fat; one sample)

5. "Common" reduced-oil DDGS (2.82 to 4.9 percent crude fat; eight samples).

These classifications imply there is much more variation in production processes used in Chinese ethanol plants than those used in U.S. fuel ethanol plants, with the common feature of partial oil extraction. However, if the samples collected in the Li et al. (2015) study are indicative of the proportion of Chinese ethanol plants extracting significant amounts of oil, it appears there is significantly more low-oil (less than 5 percent crude fat, dry matter basis) in Chinese DDGS than for U.S. DDGS.

Xue et al. (2012) compared three samples of Chinese corn DDGS produced in Shandong, Jilin, and Hebei provinces with one sample of Chinese DDGS produced from rice with bran, and two U.S. corn DDGS samples (conventional and high-protein). The rice DDGS sample had the lowest crude fat and gross energy content, and the highest crude fiber content of all samples. The Chinese corn DDGS samples had higher acid detergent fiber (ADF) content than the conventional U.S. corn DDGS sample, and lower lysine content. These researchers also reported that the lysine to crude protein ratio in Chinese corn DDGS was lower (1.93 percent) compared to U.S. corn DDGS (2.87 percent). This implies that lysine digestibility of the Chinese DDGS sample would be lower than the U.S. DDGS sample. A higher fiber, lower gross energy, and lower lysine content are key indicators of reduced feeding value of Chinese DDGS for swine and poultry, compared with the U.S. DDGS source evaluated in this study. However, the limited number of samples evaluated by Xue et al. (2012) showed there was no significant difference in metabolizable energy (ME) content between the three Chinese corn DDGS sources (3,306 kcal/kg) compared with the conventional corn DDGS source from the U.S. (3,525 kcal/kg), even though the U.S. sample numerically had 219 kcal/kg greater ME content than the average of the three Chinese DDGS sources. Furthermore, the average standardized ileal lysine digestibility of the Chinese corn DDGS samples was lower (52 percent) compared with conventional U.S. DDGS (57 percent) and U.S. high protein DDGS (60 percent).

Differences in production processes and DDGS color

The color of DDGS has become a quality factor of great importance for some buyers in the export market, and it is being used to differentiate real or perceived quality and value among DDGS sources. The color of DDGS is correlated with several nutritional components and physical characteristics. In some cases, a light colored DDGS source may infer higher lysine digestibility, xanthophyll content, and minimal lipid oxidation. On the other hand, darker colored DDGS sources may have higher concentrations of other nutrients compared with lighter colored sources. For example, adding increasing levels of solubles to the coarse grains fraction when producing DDGS sources results in higher energy, crude fat, and mineral content, with minimal effects on crude protein and amino acid content and digestibility, compared to lighter colored sources containing less solubles. Furthermore, darker colored samples appear to have higher relative phosphorus bioavailability for poultry. Particle size, moisture content and other physical properties of DDGS are also correlated with color, but the value of these relationships is more difficult to assess from a feed manufacturing and nutritional perspective.

Several years ago, some DDGS marketers and buyers developed a subjective color evaluation system using a five-color scoring card (Figure 1) to differentiate color among DDGS sources.

Although this DDGS color score card is still used in the market today, many marketers have stopped using it because it is too subjective and resulted in frequent arguments with buyers because of different interpretations of the actual color score of DDGS. As a result, many marketing contracts currently being negotiated between U.S. suppliers and foreign buyers (especially in Asian countries), contain a minimum guarantee for a quantitative measure of color (e.g. L* - lightness or darkness of color). The minimum guarantee currently being used to differentiate lightness of DDGS color is a Hunter L* greater than 50. However, increasing amounts of U.S. DDGS continue to be exported to various countries regardless of color, but for some markets demanding a guarantee of light colored DDGS (i.e. L* greater than 50), there is a significant price premium obtained for those marketers who can guarantee an L* greater than 50 in the DDGS sources they market.

Use of different production and drying processes between U.S. and Chinese ethanol plants has also led to differences in color (Figure 2). Color of DDGS U.S. DDGS generally has a lighter, golden color, which is preferred by Chinese buyers because color is considered to be a subjective indicator of greater protein and amino acid digestibility and feeding value. In fact, color is so important to some Chinese buyers that they often request a minimum guarantee for light color (L* greater than 50) in their marketing agreements. Chinese DDGS tends to be darker in color, which infers less nutritional value.

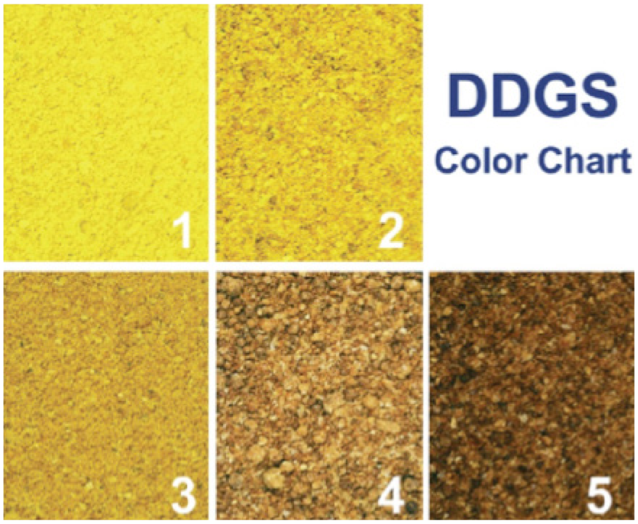

Figure 1. Example of a DDGS color score card

Figure 2. Color comparison between U.S. DDGS (left) and Chinese DDGS (right)

Jie et al. (2013) obtained 28 corn DDGS sources from several ethanol plants in 11 provinces in China and two corn DDGS samples produced in the U.S. imported into China. These researchers measured the lightness (L*), redness (a*) and yellowness (b*) of color of these samples using a HunterLab colorimeter. A low L* color score (scale of 0 to 100) indicates a darker color and L* and b* have greater correlations with lysine and amino acid digestibility (which have been used as general indicators of nutritional value) than a*. The L* values for the 28 Chinese DDGS sources ranged from 30.9 to 59.5, a* ranged from 14.6 to 27.7 and b* ranged from 35.3 to 59.8. Although only two U.S. DDGS samples were evaluated in this survey, the L* scores were 54.6 and 57.3, a* scores were 18.4 and 19.7 and b* scores were 53.3 and 55.3. Only five of the 28 Chinese DDGS samples had L* scores greater than 50, whereas both of the U.S. DDGS sources had L* scores greater than 50, indicating lighter color. Furthermore, b* value of the two U.S. DDGS sources were 53.3 and 55.3 compared with only five Chinese DDGS sources that had b* values greater than 50. Urriola et al. (2013) reported that the average L* value among 34 U.S. corn DDGS sources was 52.7 and L* values can be as high as 62.5. Therefore, another distinguishing feature of U.S. DDGS compared with the majority of Chinese DDGS sources is that U.S. DDGS sources are generally lighter in color, inferring that amino acids (components of protein) are more digestible.

Differences in Nutritional Composition, Consistency, Mycotoxins and Feeding Value of DDGS

Differences in nutrient composition and consistency

In general, energy and nutrient content of U.S. DDGS is more consistent than Chinese DDGS. This generally means nutritionists will use less conservative nutrient loading values in feed formulation, which allows them to replace more expensive ingredients to a greater extent to reduce overall diet costs, with less risk of underfeeding energy and nutrients to animals.

To provide an objective comparison of nutrient composition differences, data were summarized from three recently published reports for Chinese DDGS (Table 1). In addition, nutrient composition of U.S. corn DDGS sources were summarized from nine published reports (Table 1) and Kerr et al. (2013). All data are expressed on a dry matter (dry matter) basis (Table 1).

Generally, the crude fat, fiber and protein content contribute to overall metabolizable energy value, and crude protein content is an imprecise indicator of amino acid digestibility. Energy, amino acids and phosphorus are the three most expensive nutrition components in animal feeds. Although DDGS and other commodity ingredients are priced and traded on a moisture, crude protein, crude fat and crude fiber basis, nutritionists use estimates of metabolizable energy (ME), digestible amino acids (especially lysine) and digestible phosphorus to formulate swine and poultry diets. The majority of DDGS fed in China is used in swine and poultry diets. Therefore, the ME, digestible amino acids (especially lysine) and phosphorus content must be compared among these sources to determine if these are substantial feeding value differences.

Average moisture content of Chinese DDGS sources tends to be less than among U.S. DDGS sources, with minimal differences in average crude protein, crude fat and ash content among origins (Table 1). However, the range (variation) in crude fat content among Chinese DDGS sources is greater than among U.S. DDGS sources. In addition, the neutral detergent fiber (NDF) content of U.S. DDGS sources is lower and less variable than Chinese DDGS sources. Lower and more variable crude fat content, along with higher and more variable fiber content of Chinese DDGS compared with U.S. DDGS, suggests the metabolizable energy (ME) content of Chinese DDGS would be lower and more variable than U.S. DDGS for pigs and poultry. This is substantiated by comparing swine ME determinations of U.S. corn DDGS (Kerr et al., 2013) with swine ME determinations for Chinese DDGS (Xue et al, 2012; Li et al., 2015). Kerr et al. (2013) reported a narrower range in ME content among 15 sources of U.S. DDGS (3,266 – 3,696 kcal/kg) than Xue et al. (2012; 3,047 – 3,549 kcal/kg) and Li et al. (2015; 2,955-3,899 kcal/kg).

The starch content of Chinese DDGS sources is substantially greater than in U.S. DDGS sources (Table 1), inferring incomplete starch fermentation to ethanol, and lower amino acid digestibility. Starch can chemically react with the amino acid lysine during the DDGS drying process to form a chemical bond that renders lysine indigestible. In fact, the average standardized ileal digestibility (SID) of lysine in the Chinese corn DDGS samples (Xue et al., 2012) was lower (52 percent), compared with conventional U.S. DDGS (57 percent) and U.S. high protein DDGS (60 percent). These differences were confirmed by the summarized data from nine published reports (Table 1) indicating that the average SID lysine digestibility of U.S. corn DDGS sources is 63 percent.

The phosphorus content of Chinese DDGS is also much lower and more variable (Xue et al., 2012; Li et al., 2015) than found among U.S. DDGS sources (Kerr et al. , 2013). These results imply that for many Chinese DDGS ethanol plants, less of the condensed solubles (high in phosphorus content) is added to the coarse grains before manufacturing DDGS. Phosphorus content is another comparative advantage of U.S. corn DDGS compared with Chinese DDGS in swine and poultry diets.

Table 1. Comparison of published nutrient composition data for corn DDGS produced in China vs. U.S. (dry matter basis)

Measure	Jie et al. (2013) Chinese Corn DDGS	Xue et al. (2012) Chinese Corn DDGS	Li et al. (2015) Chinese Corn DDGS	U.S. Corn DDGS Summary[1]	Kerr et al. (2013) U.S. Corn DDGS
Moisture %	6.49 - 12.1 (8.5)	10.7 - 10.9 (10.9)	9.6 - 13.5 (11.4)	6.6 – 14.7 (11.2)	10.0 – 15.2 (12.4)
Crude protein %	25.4 - 32.3 (29.6)	26.4 – 32.0 (28.8)	28.5 - 36.8 (32.2)	27.2 - 40.8 (30.8)	27.7 – 32.7 (30.5)
Crude fat %	1.5 - 16.2 (9.3)	9.2 – 12.6 (10.5)	2.8 - 13.6 (8.6)	4.6 – 14.1 (10.6)	4.9 – 13.2 (9.7)
NDF %	45.0 - 65.8 (54.3)	43.4 – 49.5 (46.4)	31.0 - 46.6 (37.1)	30.2 – 49.6 (38.6)	28.8 – 44.0 (35.4)
Ash %	2.1 - 8.4 (5.5)	ND[2]	2.9 - 9.1 (5.4)	1.78 – 6.6 (4.4)	4.3 – 6.1 (5.1)
Starch %	ND	ND	5.3 – 16.3 (11.6)	ND	0.84 – 3.89 (2.2)
P %	ND	0.25 – 0.55 (0.39)	0.33 - 1.01 (0.75)	ND	0.71 – 0.91 (0.84)
Lysine %	ND	0.46 – 0.67 (0.56)	0.74 – 1.08 (0.91)	0.55 – 1.36 (0.94)	ND
SID[3] Lysine %	ND	0.19 – 0.29 (0.25)	ND	0.22 – 0.92 (0.59)	ND

[1] Data obtained from Fastinger and Mahan (2006); Stein et al. (2006); Pahm et al. (2008); Stein et al. (2009); Urriola et al. (2009); Jacela et al. (2010); Almeida et al. (2011); Kim et al. (2012) and Soares et al. (2012)

[2] ND = no data provided

[3] SID = standardized ileal digestible

Lysine is the first limiting amino acid in swine and poultry diets, which means it is the most likely of all amino acids to be deficient in corn and soybean meal-based diets. Therefore, lysine content and digestibility are key indicators of the nutritional value of various sources of DDGS. Furthermore, lysine content and digestibility is highly variable among Chinese and U.S. DDGS sources. Based on the limited data available for comparing lysine digestibility among Chinese and U.S. DDGS sources, it appears a greater proportion of U.S. DDGS sources have greater lysine digestibility than Chinese DDGS sources (Xue et al., 2012).

Differences in mycotoxin content in DDGS

Studies have shown that mycotoxins in feed ingredients are an ongoing concern and major problem in the Chinese feed and livestock industry. Very few Chinese grain farmers have access to grain drying equipment and proper grain storage, which leads to high prevalence and concentrations of mycotoxins that can have significant adverse health and performance effects when contaminated feed ingredients are fed to livestock and poultry. While corn and other grains produced in the U.S. and other parts of the world may contain mycotoxins, depending on climatic growing, harvest and storage conditions, the prevalence of contamination and concentrations of mycotoxins are significantly less than for grains and DDGS produced in China.

One of the major limiting factors of diet inclusion rates of DDGS is mycotoxin content. Nutritionists strive to minimize total mycotoxin content because mycotoxins cause reduced animal performance and poor health. The prevalence of mycotoxin contamination and concentrations in U.S. DDGS is much lower than Chinese DDGS. Biomin (2014) conducted a survey to collect and analyze 4,218 feed ingredient samples from over 50 countries for mycotoxins. Feed ingredients collected from Asia had the highest concentrations for most mycotoxins determined, and 65 percent of all samples contained more than one mycotoxin, compared with samples from North America, South America, Middle East and Africa. Li et al. (2014) evaluated 55 feed ingredients (including 17 DDGS samples) and 76 complete swine feeds produced in the Beijing region of China. Their results showed DDGS had the most serious mycotoxin contamination of all ingredients with 6 percent, 88 percent and 41 percent of samples exceeding Chinese regulatory limits for aflatoxin B1 (50 ppb), deoxynyvalenol (1,000 ppb) and zearalenone, respectively. In another study (Guan et al., 2011), 83 complete feed and feed ingredient samples were collected from various regions of China, which included five Chinese DDGS samples. Results from this study showed that 100 percent of the samples had positive concentrations of mycotoxins and the average concentrations of the six mycotoxins were greater than the overall average of all ingredients.

Two extensive surveys of mycotoxin contamination in U.S. DDGS have been published in recent years (Zhang et al., 2009; Khatibi et al., 2014). Zhang et al. (2009) collected 235 DDGS samples from 20 ethanol plants in the U.S. and 23 export shipping containers from 2006 to 2008. Results from this study showed:

1. None of the DDGS samples contained aflatoxins or deoxynivalenol concentrations above the U.S. FDA guidelines for use in animal feed.

2. None of the DDGS samples contained concentrations of fumonisins greater than FDA guidelines for use in dairy, beef, swine, poultry, and aquaculture feeds, and only ten percent of the samples contained concentrations of fumonisins greater than maximum levels for use in equine (horse) and rabbit (most sensitive species to fumonisins) feeds.

3. None of the samples contained detectable concentrations of T-2 toxins, and most samples contained undetectable concentrations of zearalenone.

4. Containers used for exporting DDGS did not contribute to mycotoxin production.

Another DDGS mycotoxin survey conducted by Khatibi et al. (2014) involved analyzing 141 corn DDGS samples from 78 ethanol plants located in 12 states in the U.S., for the tricothecenes deoxynivalenol (DON), 15-acetyldeoxynivalenol (15-ADON), 3-acetyldeoxynivaleniol (3-ADON), nivalenol (NIV) and zearalenone (ZON). In 2011, there was an unusually high prevalence of Fusarium spp. in the U.S. corn crop, which can infrequently occur during years with adverse weather conditions during the corn growing season. No other study has been published that has evaluated 15-ADON, 3-ADON and NIV in DDGS. Sixty-nine percent of the samples contained no detectable levels of DON, and the samples with detectable levels contained one to five ppb DON. Only 5 percent of the samples were above the FDA advisory levels for swine. Eighty-five percent of samples had no detectable concentrations of 15-ADON, and none of the samples contained detectable levels of 3-ADOn or NIV. Only 19 percent of the samples contained detectable concentrations of ZON.

Results from these studies indicate there is much lower risk and concentrations of mycotoxins in U.S. DDGS than found in Chinese DDGS samples (Guan et al, 2011; Li et al., 2014). As a result, U.S. DDGS can be used at higher diet inclusion rates than Chinese DDGS while minimizing the risk of exceeding total diet mycotoxin concentrations above recommended levels.

Differences in feeding value and use of DDGS in animal feeds

The majority of DDGS used in China is consumed in the swine and poultry industries. U.S. DDGS has several advantages over Chinese DDGS, particularly for swine, poultry and dairy cattle. Because Chinese DDGS has greater prevalence and concentrations of mycotoxins than U.S. DDGS, the risk of reduced animal performance and health, as well as mycotoxin contamination in cow's milk), is significantly reduced by feeding U.S. DDGS. Furthermore, U.S. DDGS is generally less variable in energy and nutrient content (corn is the primary feedstock used and production processes are generally similar among ethanol plants), and has higher lysine digestibility and phosphorus content, making it more valuable in feed formulations than Chinese DDGS.

Jewison and Gale (2012) summarized estimates of diet inclusion rates for various animal species (Table 2). Jewison and Gale (2012) also estimated total DDGS consumption by species in China to be 10 percent for dairy cattle, 20 percent for swine, 60 percent for poultry and 10 percent for aquaculture.

Potential feed safety risks of Chinese DDGS

Due to melamine contamination of infant formulas and other food safety scandals that have occurred in China products in recent years, there is widespread global concern and skepticism about feed and food safety of Chinese products. Gale and Buzby (2009) indicated that food safety risks are difficult to manage in Chinese food products because of weak enforcement of food safety standards by the Chinese government, heavy use of agricultural chemicals and extensive environmental pollution. As a result, technology has been developed to distinguish country of origin of DDGS and other feed products (Tena et al., 2015). Use of NIR analysis enabled excellent results in discriminating DDGS samples from China vs. pooled samples from Europe and the U.S. (Tena et al., 2015). This suggests there are distinct composition and quality differences among DDGS samples produced in China compared with those produced in Europe and the U.S.

Table 2. Comparison of the percentage of diet inclusion rates for dairy, beef, swine, and poultry in China and the U.S. (Jewison and Gale, 2012)

Species	China	United States
Dairy cattle	20 to 30 percent	10 to 20 percent
Beef cattle	No Data Available	10 to 40 percent
Swine	10 to 12 percent	10 to 50 percent
Poultry	5 to 10 percent	5 to 10 percent

Global Market Demand for U.S. DDGS

Exports of U.S. DDGS have been increasing since 2007 as U.S. ethanol and DDGS production have also increased, where more than 31 different counties have imported U.S. DDGS. The major export markets for U.S. DDGS are Mexico, various countries in Asia, Canada and Turkey. This growth in global demand indicates U.S. DDGS is an economically competitive feed ingredient in many countries on five continents, and is attractive because of its high quality and excellent nutritional value compared to other alternative feed ingredients.

Because DDGS is a high energy, moderate protein feed ingredient, it tends to follow corn price more closely than soybean meal price. U.S. DDGS prices are based on the global market, with minimum guarantees of crude protein and crude fat content. Historically, U.S. DDGS has been priced based on a composite of protein and fat content "profat" minimum guarantees. However, partial extraction of corn oil prior to manufacturing DDGS has complicated the use of this composite measure to establish price because protein content does not increase to the same extent as the decline in crude fat content in reduced-oil DDGS. Therefore, many buyers and sellers are establishing price based on separate minimum guarantees for crude protein and crude fat.

Chinese tariff and tax policies are important factors that affect imports of DDGS compared with other feed ingredients (Jewison and Gale, 2012). As of 2012, DDGS was not subjected to import quotas, exempt from value-added taxes (VAT), and were assessed a relatively low (five percent) tariff. In contrast, imports of corn are regulated by a tariff rate quota system, and subjected to a one percent tariff and 13 percent VAT.

Chinese feed ingredient buyers are very price sensitive. The large amounts of U.S. DDGS purchased by Chinese buyers in recent years can sometimes be attributed to a lower price compared with Chinese corn, but better quality, consistency, and nutritional value of U.S. DDGS compared with Chinese DDGS appear to be very important factors. As an example, Jewison and Gale (2012) indicated that from June to December, 2011, the average price of U.S. DDGS imported to China was 19 percent lower than the cost of domestic Chinese corn and 35 percent lower than soybean meal. However, during this time period, the price of domestic Chinese DDGS (northeast China) was 13 percent lower than the price of imported U.S. DDGS.

However, Chinese DDGS buyers are willing to pay a premium price for imported U.S. DDGS because of its improved quality and consistency compared with Chinese DDGS (Jewison and Gale, 2012). Chinese buyers prefer the lighter, and more golden color of U.S. DDGS compared with Chinese DDGS because it has greater feeding value, and they have fewer problems with customer acceptance of the color of finished complete feed products.

Due to high demand for raw materials for animal feed production, very little, if any DDGS produced in China is exported. Corn production and supply is most abundant in northeast China, which is also where the majority of domestic DDGS is produced (Jewison and Gale, 2012). However, a high proportion of swine and poultry production and feed manufacturing occurs in the southern region of China, causing high transportation costs to move these ingredients to this region where they are consumed. As a result, corn prices in southern China (e.g. Guangdong) are 12 to 15 percent greater than in northeast China (Jewison and Gale, 2012). Therefore, southern China is the main geographical location that uses imported U.S. DDGS.

As a result, imported U.S. DDGS tends to be used in areas in close proximity to the ports due to transportation costs to move to the interior of China. For this reason, Chinese DDGS production is used to a greater extent in regions near the ethanol plants.

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CHAPTER 9

Physical and Chemical Characteristics Related to Handling and Storage of DDGS

Introduction

COMPARED TO OTHER FEED INGREDIENTS, DDGS HAS SOME UNIQUE PHYSICAL AND CHEMICAL CHARACTERISTICS that affect storage and handling characteristics. The use of DDGS in livestock, poultry, and aquaculture feeds has created challenges in several stages of the ingredient handling, transport, storage, and manufacturing including difficulty unloading rail cars, containers and bulk vessels; difficulty with moving and storing DDGS using conventional feeder screws and storage bins; pellet quality and production rates (discussed in detail in Chapters 17, 22 and 25), and managing nutrient variability to avoid the risk of compound feeds not meeting desired nutrient specifications (discussed in detail in Chapters 7, 21 and 24).

Proper feed ingredient storage is essential for preserving nutritional value and preventing spoilage. The original condition of a feed ingredient is the most important factor affecting preservation of quality during storage, and is influenced by moisture content, relative humidity and temperature (Mills, 1989). Moisture within a feed ingredient ultimately reaches equilibrium with the air within and between particles over time, and depending on the conditions, may lead to the growth of molds and other deleterious microorganisms (Mills, 1989). Maximum acceptable moisture concentrations of grains have been established and vary among grain type for different storage periods (Mills, 1989). Furthermore, maximum relative humidity levels have been established to prevent mold growth (less than 70 percent), bacteria growth (less than 90 percent), and storage insects (less than 60 percent; Mills, 1989) of grains. However, it is important to remember moisture and relative humidity interact with temperature in the storage environment. High temperatures of grain and feed ingredients at the time of loading a storage bin can be maintained for many months if the mass is aerated. Temperature and moisture content determine the extent of enzymatic and biological activities of the grain or ingredient, and temperature differences within the stored mass can increase the risk of mold growth through moisture migration (Mills, 1989). Unfortunately, no studies have been conducted to determine optimal storage conditions to maintain DDGS quality and prevent spoilage over extended periods of time or under various climatic conditions. As a result, it is generally assumed drying DDGS to a moisture content less than 12 percent is acceptable under moderate temperatures and humidity during storage.

Storage Bin Space Allocation

When a new feed ingredient is used for the first time in a commercial feed mill, appropriate storage space must be identified or constructed. It is unusual a feed mill would have an open bin or unused storage space to accommodate a new ingredient. While a simple solution is to decide to discontinue using an existing ingredient and designate that storage bin for the new ingredient, it is very difficult to do this without disrupting the feed manufacturing process (Behnke, 2007). If the bin volume, hopper configuration, and feeder screw design are not suitable for the new ingredient, exploring other options are necessary (Behnke, 2007). When deciding feed ingredient allocation to storage bins, one of the most important considerations is determining the expected diet inclusion rates in all feeds manufactured to calculate daily or monthly usage rate and frequency of use (Behnke, 2007). Perhaps the second most important consideration is related to the physical properties such as bulk density and flow characteristics of the ingredient.

Bridging, Caking and Flowability of DDGS

One of the greatest challenges for handling DDGS is its propensity for bridging, caking, and poor flowability when attempting to unload it from rail cars, containers, and bulk vessels. Flowability is defined as "the relative movement of a bulk of particles among neighboring particles or along the container wall surface" (Pelig, 1977). Unfortunately, some DDGS sources have poor flowability and handling characteristics (Bhadra et al., 2008), which has prevented routine use of rail cars for transport, which has led to the development of specially designed unloading equipment for bulk vessels and containers, and has limited its use in livestock and poultry diets because of bridging in bulk storage containers.

Many factors affect the flow of a bulk ingredient (Peleg, 1977) and no single measurement adequately describes flowability (Bhadra et al., 2008). However, while moisture content of DDGS and the relative humidity of the environment are the major contributing factors to bridging, caking and poor flowability, other factors such as particle size, proportion of condensed solubles added to the grains fraction before drying, dryer temperature, moisture content at dryer exit, and others have also been attributed to this problem (Ganesan et al., 2008a,b,c). Moisture content of DDGS is generally between 10 to 12 percent to avoid spoilage due to mold growth during long-term storage. However, DDGS is also hygroscopic and can gradually increase in moisture content during exposure to humid conditions over a long storage period (Ganesan et al., 2007). The hygroscopic properties of DDGS can lead to bridging, caking and reduced flowability during transport and storage (Rosentrater, 2007).

Because there is limited storage capacity for DDGS at ethanol plants, it is sometimes loaded into transport vessels within a few hours after it exits the dryer before moisture equilibrates. When this occurs, DDGS will harden and become a solid mass in trucks, rail cars and containers, making it very difficult to unload. However, if warm DDGS is allowed to cool so the moisture can equilibrate before loading, flowability is greatly improved. Most ethanol plants today have implemented a minimum 24-hour "curing," or moisture equilibration period before loading to avoid bridging and caking to prevent damage and cost to rail cars during unloading. Ideally, holding DDGS for five to seven days would allow complete moisture equilibration to occur so the liquid bridges formed in the cooled mass can be broken, which will minimize further handling difficulties (Behnke, 2007). Unfortunately, the majority of ethanol plants have only about two to three days of storage capacity during continuous operations, resulting in an inability to provide a five to seven day time period for adequate moisture equilibration.

The equilibrium relationship between moisture content and relative humidity of the surrounding environment for bulk solids is affected by sorption isotherms. A sorption isotherm indicates the corresponding water content at a specific, constant temperature at a specific humidity level. Therefore, as the relative humidity in the storage environment increases, the sorption increases and causes formation of a liquid bridge between particles (Mathlouthi and Roge, 2003). Adsorption (ability to hold water on the outside or inside surface of a material) and desorption (release of water through or from a surface) of moisture under humid conditions is complex and is affected by the carbohydrate, sugar, protein, fiber and mineral concentrations of a feed ingredient (Chen, 2000). Understanding this relationship for DDGS is important in determining critical moisture and relative humidity levels that may cause bridging and caking of DDGS during transport and storage.

Kingsly and Ileleji (2009) showed formation of liquid bridges occurred in DDGS when the relative humidity reached 60 percent. At a relative humidity of 80 percent, DDGS reached maximum moisture saturation, and at 100 percent relative humidity, the liquid bridge formed by adsorption of moisture hardened and led to the formation of a solid bridge as humidity was reduced. These results indicate that increased relative humidity during transport and storage causes irreversible bridging between DDGS particles and leads to particle aggregation (clumping), caking, and reduced flowability.

Pelleting DDGS is another approach a few ethanol plants have attempted to use to improve bulk density and flowability. Researchers at Kansas State University evaluated the use of various conditioning temperatures and pellet die sizes on ease of pelleting, physical properties, and flow characteristics of DDGS, and showed almost any combination of pelleting conditions improved flowability of DDGS (Behnke, 2007). However, this approach has not been implemented in the U.S. ethanol industry for several reasons. First, it would require additional cost for existing ethanol plants because of the need to purchase, install, and operate expensive boilers and pellet mills; would require additional personnel training and labor cost; and would require additional storage space. Furthermore, most DDGS customers are reluctant to purchase pelleted DDGS because they may perceive it as adulterated with other "fillers," may reduce amino acid and nutrient digestibility because of the thermal treatment during the pelleting process and the added cost of re-grinding the pellets before adding it to other ingredients to manufacture complete feeds in commercial feed mills.

Effects of DDGS oil content on flowability

Physical properties of conventional high-oil (Rosentrater, 2006), reduced-oil (Ganesan et al. 2009) and low-oil (Saunders and Rosentrater, 2007) DDGS have been evaluated. Ganesan et al. (2009) showed reduced-oil DDGS may have improved flow properties compared to conventional high-oil DDGS, but both types were classified to have "cohesive" properties, which suggests that regardless of oil content, DDGS is prone to bridging and caking problems during long-term storage. These researchers suggested that chemical composition and particle surface morphology (roughness, size and shape) may have a greater effect of DDGS flowability than oil content.

As previously discussed, extended storage time for more complete moisture equilibration and pelleting DDGS are not currently viable options for preventing handling and flowability challenges, several new unloading equipment designs have been developed and are being used to facilitate unloading of DDGS from rail cars and containers. For example, stationary devices are located above a rail car pit and use a steel spear to break the hardened mass before unloading. Although these methods improve the time of unloading, they also increase labor and equipment cost. Furthermore, many commercial feed mills have chosen to use flat storage rather than bin or silo storage of DDGS to avoid flowability problems with handling DDGS. The main advantage of flat storage is it adequately addresses the flowability problems and requires lower short-term capital investment compared with constructing silos. However, flat storage is much more labor intensive, requires front-end loading equipment to move the material, increases the risk of contamination with other ingredients within the storage facility and increases "shrink" losses.

Effects of adding flow agents to DDGS

The addition of various flow agents has been another approach attempted to improve flowability of DDGS, but only a few studies have been conducted to evaluate their effectiveness. Ganesan et al. (2008a) evaluated the effects of adding calcium carbonate to DDGS comprised of varying moisture and condensed distillers solubles content in a laboratory setting, and showed no benefits for improving flowability. Johnstonet al. (2009) evaluated flowability after adding dry matterX-7 (2.5 kg/metric ton; Delst, Inc. Temecula, CA), 2 percent calcium carbonate (ILC Resources, Inc., Des Moines, IA), or 1.25 percent clinoptilolite zeolite (St. Cloud Mining Co., Winston, NM) to DDGS containing either 9 percent or 12 percent moisture. After flow agents were added and mixed with DDGS at the ethanol plant, trucks were loaded, traveled 250 km, were parked and motionless for 60 hrs, followed by transporting another 250 km back to the ethanol plant where it was unloaded, and flowability measurements were obtained. Outdoor temperatures on each of the four days (over a two month period) ranged from 12.9 to 27.8°C, and outdoor relative humidity ranged from 34 to 67 percent. Average particle size of the DDGS source used in this experiment ranged from 584 to 668 µm. The flow rate during unloading of each truckload of DDGS was improved by adding zeolite (558 kg/min) compared with dry matterX-7 (441 kg/min), but these treatments were not different from the control (no flow agent; 509 kg/min) and the calcium carbonate (512 kg/min) treated DDGS loads. Furthermore, flowability score (1 = free flowing, 10 = badly bridged) was improved when zeolite was added to DDGS (4.0) compared with the control (6.0), dry matterX-7 (6.5) and calcium carbonate (5.5). Moisture content at the time of loading was the most important predictor (explained 70 percent of the variation) of flow rate of DDGS, where each 1 percent increase in moisture content from 9 percent, decreased unloading rate by 100 kg/min. Similar results were reported by Ganesan et al. (2008b) where increasing moisture content of DDGS reduced flowability. Ganesan et al. (2008b) also reported that as the Hunter b* score (yellowness of color) increased in DDGS, flow rate also increased, but this only accounted for 4 percent of the variation in flow rate. These results indicate that the most effective criteria from improving flow rate in DDGS is to dry it to lower (9 percent) moisture content, and the addition of dry matter X-7, calcium carbonate and zeolite had no significant benefits for improving flow of DDGS during unloading from trucks.

Effects of Bulk Density on Freight Weight and Particle Segregation of DDGS

Maintaining consistent bulk density of DDGS when loading rail cars and containers has been a challenge for both marketers and buyers because of the desire to achieve consistent freight weights in sequentially loaded rail cars and containers to minimize shipping costs (Ileleji and Rosentrater, 2008). Bulk density varies among DDGS sources, has been reported to range from 391 to 496 kg/m^3 (Rosentrater, 2006) and 490 to 590 kg/m^3 (Bhadra et al., 2009). Clementson and Ilelejie (2010) suggested differences in bulk density observed during loading of rail cars may be due to particle segregation. This is likely to occur because DDGS is a granular bulk solid with particles of various sizes, densities and morphological characteristics found in the structural components of corn grain (Ileleji et al., 2007). Particle segregation was shown to occur during handling and gravity discharge of DDGS (Ileleji et al., 2007; Clementson et al., 2009). Clementson and Ilelejie (2010) conducted a study to evaluate bulk density variation of DDGS when filling and emptying hoppers to simulate loading of rail cars at an ethanol plant, and showed that variation in bulk density occurred as DDGS is loaded and emptied, and was mainly attributed to particle segregation. These researchers showed that after filling, the finer, smaller and denser particles were concentrated in the center of the hopper, while the larger, coarser and less dense particles were concentrated on the sides of the hopper. This phenomenon not only causes variation in bulk density during transloading of DDGS, but it should also be considered when sampling DDGS for nutrient analysis because the location of sampling can influence the mixture of segregated particles and ultimately affect the analytical results (Clementson et al., 2009).

Effect of Storage Bin Design and Particle Size on Flowability of DDGS Diets

Effects of feed storage bin design

Flowability of DDGS is not only a challenge during loading, transport, storage and feed manufacturing, but it can also create challenges on swine farms when DDGS diets are fed in meal form. Suboptimal feed flow can reduce the rate of feed delivery to feeders and bridge in feeders which can lead to out-of-feed events, which can increase stress and the likelihood of gut health problems and reduced growth performance in pigs (Hilbrands et al., 2016). This problem is a greater concern when there is an economic incentive to increase diet inclusion rates of DDGS to 30 percent or more in swine diets, especially when meal diets with small particle size are fed to improve feed conversion of pigs, which is commonly done in the U.S. Storage bin design can be a significant cause or a potential solution to the flowability problems with feed containing DDGS. Hilbrands et al. (2016) conducted a study to evaluate feed flow from three commercially available feed storage bins. The three bin designs consisted of: 1) a galvanized steel, smooth-sided, seamless bin with a 60 degree round discharge cone (Steel60), 2) a galvanized, corrugated steel bin with a 67 degree round discharge cone (Steel67), and 3) a white, polyethylene bin with a 60 degree round discharge cone (Poly60). The bin styles were chosen to represent differences in slopes of the sides of discharge cones, as well as different construction materials in the bin walls. Diets used in this study contained 55 percent corn, 35 percent soybean meal, 40 percent DDGS, and 2 percent minerals and vitamins, and were ground to an average particle size ranging from 736 to 1,015 microns. The study was conducted in two experiments during the summer and fall seasons. During the summer season, daily high and low temperatures ranged from 30.9°C to 16.6°C, and daily relative humidity ranged from 39.4 to 100 percent. During the fall season, daily high and low temperatures ranged from 2.9°C to 23.7°C, and daily relative humidity ranged from 23.3 to 92.7 percent.

Feed flow rate out of bins was faster from Poly60 bins compared with Steel60 bins, with feed flow rate from Steel67 bins being intermediate (Table 1). However, it was interesting the Steel60 bins with the slowest flow rate required the fewest number of taps to keep feed flowing during discharge. As shown in Table 2, the presence of a passive agitator increased feed flow rate among all bin designs compared with bins without agitators, but the presence of agitators in Poly60 bins resulted in greater feed flow rate than the presence of agitators in steel bins. However, unlike results in the first experiment, there was no difference in the number of taps required to establish feed flow among the six bin design combinations.

These results indicate that feed bin design affects the flow rate during discharge of meal diets containing 40 percent DDGS. The Poly60 bin provided the best feed flow and highest discharge rates compared with the steel bin designs evaluated, and installing passive agitators increase feed flow in all bin designs.

Table 1. Effect of bin design and temperature and humidity conditions in the headspace on feed flowability (adapted from Hilbrands et al., 2016)[1]

Experiment 1

Measurement	Steel60	Poly60	Steel67
Average temperature, °C	23.6	22.9	22.6
Average humidity %	55.3	54.7	53.9
Feed flow, kg/min	603^{a}	737^{b}	663^{ab}
Taps required[2]	3.8^{a}	7.5^{b}	6.0^{b}
Flowability score[3]	3.7^{a}	4.9^{b}	4.2^{ab}

[1] Means with different superscript letters are different (P less than 0.05).

[2] Number of taps on the side of the bin required during discharge.

[3] Subjective score assigned to flowability (1 = free flowing, 10 = completely bridged)

Table 2. Effect of bin design, passive flow assist agitators, and temperature and humidity conditions in the headspace on feed flowability (adapted from Hilbrands et al., 2016)[1]

Experiment 2

Measurement	Steel60		Poly60		Steel67	
	No agitator	Agitator	No agitator	Agitator	No agitator	Agitator
Avg. temperature, °C	20.1	20.4	19.6	19.5	19.0	18.8
Avg. humidity %	58.3	65.0	65.0	61.3	61.1	63.8
Feed flow, kg/min	827a	827a	831a	970b	807a	880a
Taps required[2]	2.1	2.0	5.2	2.5	3.2	2.0
Flowability score[3]	2.3	2.6	4.2	2.9	3.7	2.3

[1] Means with different superscript letters are different (P less than 0.05).

[2] Number of taps on the side of the bin required during discharge.

[3] Subjective score assigned to flowability (1 = free flowing, 10 = completely bridged)

Effects of particle size

Particle size among DDGS sources is highly variable, with an average of 660 µm and a standard deviation of 440 µm (Liu, 2008). Particle size of DDGS not only contributes to its flow properties (Ganesan et al., 2008a,b,c), but also affects metabolizable energy (ME) content and nutrient digestibility (Mendoza et al., 2010). To further evaluate the effects of DDGS particle size on ME content and nutrient digestibility for growing pigs, Liu et al. (2012) determined the ME content and nutrient digestibility of the same source of DDGS ground to three particle sizes (818 µm = coarse, 594 µm = medium, and 308 µm = fine). These researchers also evaluated flowability of diets containing 30 percent DDGS. As expected, ME content of DDGS improved as the particle size was reduced, where each 25 µm reduction in average particle size (between 818 and 308 µm) increased the ME content of the diet by 13.5 kcal/kg of dry matter. However, there were no effects of DDGS particle size on nitrogen and phosphorus digestibility. Diet flowability was reduced in the 30 percent DDGS diets compared with the control corn-soybean meal diet, and was lowest in the diet containing finely ground DDGS (determined by measuring the drained angle of repose). When flowability of these diets was determined using poured angle of repose as the measurement criteria, there were no differences in flowability between the control and 30 percent DDGS diets, nor were there differences among diets containing different particles sizes of DDGS.

Risk of Mold Growth and Mycotoxin Production During Storage of DDGS

Toxigenic fungal species of molds can develop on grains while growing in fields before harvest, as well as after harvest during storage (Suleiman et al., 2013). Consequently, fungal species are often classified as field fungi or storage fungi (Barney et al., 1995). Field fungi can infect corn grains and produce mycotoxins before harvest at moisture content between 22 to 33 percent, relative humidity greater than 80 percent, and over a wide range of temperatures (10 to 35°C; Williams and MacDonald, 1983; Montross et al., 1999). Most field fungi do not survive during storage, but some species can continue to grow under appropriate storage conditions (Sanchis et al., 1982). Storage fungi also originate from the field and can replace field molds that infected corn grain prior to harvest (Reed et al., 2007). As shown in Table 3, storage fungi require a relative humidity greater than 70 percent, and moisture content greater than 12 percent for corn grain (Montross et al., 1999). Additional fungal species may also be introduced after harvest and include Fusarium spp., Rhizopus spp., and Tilletia spp. (Williams and MacDonald, 1983; Barney et al., 1995). Because DDGS is produced from corn grain, it is reasonable to assume these same molds may be present in DDGS. However, due to the unique physical and chemical properties of DDGS, it is unknown if these relative humidity and moisture conditions apply as they do for corn grain. In fact, DDGS may be more susceptible to mold growth than corn grain because mechanical damage of corn grain during and after harvest can provide entry for fungal spores (Dharmaputra et al., 1994), and broken corn kernels and foreign material promote growth of storage molds (Sone, 2001). For more information on recommended analytical methods to determine mycotoxins in DDGS, see Chapter 7.

Lipid Peroxidation of DDGS Sources

Effects of feeding peroxidized lipids to pigs and broilers

Corn DDGS contains the highest lipid concentrations of most common feed ingredients used in animal feeds around the world. Lipid peroxidation is a complex chemical chain reaction induced by heat, oxygen, moisture and transition metals (e.g. Cu and Fe), where free-radicals are converted to toxic aldehydes and other compounds (Shurson et

Table 3. Relative humidity and moisture content that support growth of common storage molds in cereal grains at 25°C to 27°C (adapted from Montross et al., 1999)

Fungal species	Relative humidity %	Moisture content %
Aspergillus halophilieus	68	12 – 14
Aspergillus restrictus	70	13 – 15
Aspergillus glaucus	73	13 – 15
Aspergillus candidus	80	14 – 16
Aspergillus ochraeus	80	14 – 16
Aspergillus flavus	82	15 – 18
Aspergillus parssiticus	82	15 – 18
Penicillium spp	80 – 90	15 – 18

al., 2015). Corn oil present in DDGS consists primarily of polyunsaturated fatty acids, particularly linoleic acid (C18:2, 58 percent), which is highly susceptible to peroxidation (Frankel et al., 1984). When lipids are heated at relatively high temperatures, large quantities of secondary lipid peroxidation products are produced including aldehydes, carbonyls and ketones (Esterbauer et al., 1991). Drying temperatures used to produce DDGS can be as high as 500°C, which makes it susceptible to lipid peroxidation. All of the pro-oxidation conditions (heat, oxygen, moisture, and transition minerals) are present in ethanol plants that produce DDGS, and DDGS may be further exposed to these factors during transport, storage, and manufacturing complete feeds in commercial feed mills. Therefore, there is some concern about the extent of peroxidation in DDGS after production, and during transport and long-term storage.

Feeding peroxidized lipids to pigs and broilers has been shown to reduce growth performance and increase oxidative stress. Hung et al. (2017) conducted a meta-analysis using swine and poultry data from 29 publications that showed an average reduction in ADG (5 percent), ADFI (3 percent), gain:feed (2 percent) and serum of plasma vitamin E (52 percent), while increasing serum TBARS (thiobarbituric acid reactive substances; 120 percent) across all studies. Recent reviews by Kerr et al. (2015) and Shurson et al. (2015) provide a comprehensive summary of biological effects of feeding peroxidized lipids to swine and poultry and the challenges of measuring peroxidized lipids and interpreting the results. The lipid peroxidation section in Chapter 24 of this handbook describes the results from some recent swine feeding trials (Song et al., 2013; Song et al., 2014; Hanson et al., 2015a) which showed inconsistent growth performance responses from feeding a highly peroxidized DDGS diet to pigs.

Survey of lipid peroxidation indicators among DDGS sources

Song and Shurson (2013) evaluated measures of lipid peroxidation and color of 31 corn DDGS sources obtained from ethanol plants in nine states in the U.S., and compared these values with a sample of corn as a reference (Table 4). Peroxide value and TBARS (thiobarbituric acid reactive substances) are two common measures of lipid peroxidation used in the feed industry for many years. However, these peroxidation indicators have several limitations like all other measures of peroxidation and therefore, are not always reflective of the true extent of peroxidation of lipids (Hung et al., 2017; Shurson et al., 2015). Currently, there are no standards or guidelines for measuring lipid peroxidation in feed ingredients. However, Wang et al. (2016) suggested that 4-hydroxynonenal and a ratio of select aldehydes provide better estimates of the actual extent of peroxidation in vegetable oils. Unfortunately, these analytical procedures are not commonly used in commercial laboratories.

Peroxide value (PV) has been used to estimate the extent of peroxidation during the initiation phase of the peroxidation process. The PV of the DDGS samples was highly variable (CV = 97.5 percent), with a minimum value of 4.2 and maximum value of 84.1 meq/kg oil. The TBARS value has been used as an estimate of the extent of lipid peroxidation during the propagation phase of peroxidation, which is when the majority of aldehydes are produced. There was less variability (CV = 43.6 percent) in TBARS values among DDGS sources compared with PV values, and ranged from 1.0 to 5.2 ng MDA equiv./mg oil. Both PV and TBARS were greater in DDGS samples compared with the corn reference values, expected because of the thermal processing involved in producing DDGS. Moderate negative correlations were observed for

Table 4. Summary of lipid peroxidation indicators of oil extracted from 31 corn DDGS samples and DDGS color (adapted from Song and Shurson, 2013)

DDGS						
Measure	Corn	Average	Median	Minimum	Maximum	CV %
Peroxide value, meq/kg oil	3.1	13.9	11.7	4.2	84.1	97.5
TBARS[1], ng MDA equiv./mg oil	0.2	1.9	1.7	1.0	5.2	43.6
Color						
L*[2]	83.9	54.1	54.9	45.2	58.1	4.6
a*[3]	2.6	10.9	10.8	9.3	12.4	7.2
b*[4]	20.0	37.3	37.5	26.6	42.7	8.8

1TBARS = thiobarbituric acid reactive substances

2L* = a greater value indicates a lighter color.

3a* = a greater positive value indicates a more reddish color.

4b* = a greater positive value indicates a more yellowish color.

colorometric measures between L* and PV (r = -0.63) and b* and PV (r = - 0.57), with slightly greater negative correlations between L* and TBARS (r - -0.73) and b* and TBARS (r = -0.67). These results suggest darker colored and less yellow colored DDGS samples may be more peroxidized.

However, subsequent studies involving the most peroxidzed DDGS source to wean-finish pigs (Song et al., 2014), and sows and their offspring through the nursery phase (Hanson et al., 2016) had no detrimental effects on growth performance. The lack of growth performance responses in these studies may have been a result of the naturally high antioxidant compounds (tocopherols, ferulic acid, lutein, zeaxanthin; Shurson, 2017) present in DDGS, and conversion of sulfur compounds into endogenous antioxidants.

Effects of commercial antioxidants in preventing lipid peroxidation in DDGS

Synthetic antioxidants are commercially available and used to minimize peroxidation in feed fats and oils (Valenzuela et al., 2002; Chen et al., 2014). The most commonly used synthetic antioxidants include t-butyl-4-hydroxyanisole (BHA), 2,6-di-t-butylhydroxytoluene (BHT), t-butylhydroquinone (TBHQ), ethoxyquin, and 2,6-di-ter-butyl-4-hydroxymethyl-phenol (Guo, et al., 2006).

Only one study has been published to evaluate the effectiveness of adding synthetic antioxidants to high- (13 percent crude fat) and low- (5 percent crude fat) oil DDGS (Hanson et al., 2015b). Samples of these two DDGS sources contained either no added synthetic antioxidants (control), or 1,000 mg/kg TBHQ (Rendox; Kemin Industries, Des Moines, IA), or 1,500 mg/kg of ethoxyquin and TBHQ (Santoquin; Novus International, St. Louis, MO). Samples were stored in a temperature (38°C) and relative humidity (90 percent) controlled environmental chamber for 28 days, and subsamples were collected on day 0, 14 and 28 to determine the extent of lipid peroxidation. Results of this study showed significant lipid peroxidation occurred and increased during the 28-day storage period, and the extent of peroxidation was greatest in the high-oil DDGS source compared with the low-oil DDGS source (Table 5). However, the addition of either Rendox or Santoquin to either the high- or low-oil DDGS sources reduced peroxidation by about 50 percent. Therefore, these results show that the addition of either Rendox or Santoquin is effective in reducing lipid peroxidation in DDGS when stored up to 29 days in hot, humid conditions. In addition, moisture content of DDGS sources increased from 10.2 percent to 21.4 percent during the 28-day storage period, which led to significant mold growth in all samples.

Table 5. Interactive effects of oil content of DDGS, antioxidant, and sampling day on lipid peroxidation of DDGS source stored at 38°C and 90 percent relative humidity (adapted from Hanson et al., 2015)

Item	High Oil DDGS			Low Oil DDGS		
	Control	Rendox	Santoquin	Control	Rendox	Santoquin
Peroxide value, mEq/kg oil						
Day 14	7.1^{a}	3.1^{bc}	3.6^{b}	4.5^{d}	2.7^{c}	2.8^{c}
Day 28	31.4^{a}	13.9^{bc}	15.4^{b}	20.5^{d}	11.7^{bc}	13.6^{bc}
TBARS[1], mg MDA[2] Eq/kg oil						
Day 14	5.1^{a}	2.9^{cd}	2.4^{d}	3.8^{bc}	2.4^{d}	2.3^{d}
Day 28	21.1^{a}	9.5^{b}	9.0^{b}	14.3^{d}	11.0^{bc}	10.1^{bc}
p-Anisidine value[3]						
Day 14	3.9^{a}	1.0^{b}	1.0^{b}	3.8^{a}	0.7^{b}	1.0^{b}
Day 28	9.1^{a}	3.4^{bc}	2.9^{bc}	9.5^{a}	5.0^{b}	4.3^{b}

^{a,b,c,d}ry matteereans within a row with different superscripts are different (P less than 0.05).

[1] TBARS = thiobarbituric acid reactive substance

[2] MDA = malondialdehyde

[3] p-anisidine value has no units

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CHAPTER 10

DDGS Color IS NOT a Reliable Indicator of DDGS Quality and Nutritional Value

Why is DDGS Color a Quality Issue?

THERE ARE NO GRADING SYSTEMS, OR DEFINED AND REGULATED QUALITY STANDARDS FOR DDGS like there are for corn (e.g. U.S. #2) and other U.S. grain commodities. As a result, misunderstandings can occur between buyers and sellers of U.S. DDGS worldwide. Establishing prices, writing contracts and meeting expectations are problematic in the absence of quality standards. While professionals in industry, government, and academia have discussed, and attempted to develop quality standards for DDGS during the past decade, attempts failed due to disagreements on the need for defined quality standards and perhaps the fear of increased transparency and ability to distinguish quality and value differences among DDGS sources. Most U.S. DDGS marketers prefer to focus only on maximum guarantees for moisture and fiber, and minimum guarantees for fat and protein. However, because of variability in nutrient content and quality among U.S. DDGS sources, many international DDGS buyers often demand more guarantees for specific quality attributes to minimize their risk of obtaining co-products that don't meet their expectations.

The color of DDGS has become a quality factor of great importance for some buyers in the export market, and it is being used to differentiate real or perceived quality and value among DDGS sources. Several years ago, some DDGS marketers and buyers developed a subjective color evaluation system using a five-color scoring card (Figure 1) to differentiate color among DDGS sources. Although this DDGS color score card is still used in the market today, many marketers have stopped using it because it is too subjective and resulted in frequent arguments with buyers because of different interpretations of the actual color score of DDGS. As a result, many marketing contracts now being negotiated between U.S. suppliers and foreign buyers (especially in Asian countries) contain a minimum guarantee for a quantitative measure of color (e.g. L* - lightness or darkness of color). The minimum guarantee currently being used to differentiate lightness of DDGS color is a Hunter L* greater than 50 to meet some buyers expectations. Increasing amounts of U.S. DDGS continue to be exported to various countries regardless of color, but for some markets demanding a guarantee of light-colored DDGS (i.e. L* greater than 50), there is a significant price premium obtained for those who can guarantee an L* greater than 50 in the DDGS sources they market.

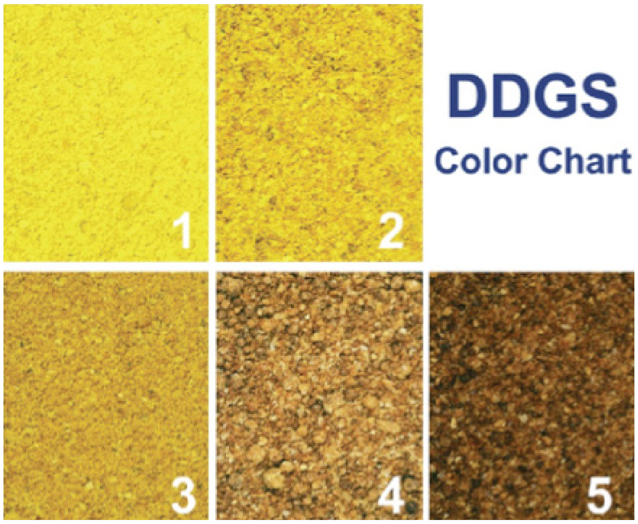

Figure 1. Example of a DDGS color score card

As a result, some U.S. suppliers have become frustrated and question the value of using DDGS color as an indicator of quality, especially if they are unable to supply DDGS that meets the buyer's color expectations. Therefore, the purpose of this paper is to define DDGS quality and the role of using color as a quality indicator in the marketplace, and provide a description of a variety of other quality characteristics and measurements that can be used to assess DDGS value.

How Do We Define Quality?

There are many definitions of quality. Quality is defined as an essential character or inherent feature that represents a degree of excellence, superiority, or a distinguishing attribute (http://www.merriam-webster.com/dictionary/quality).

In the context of business (http://www.businessdictionary.com/definition/quality.html), quality has been defined as a general measure of excellence or state of being free from defects, deficiencies, and significant variations. The ISO 8402-1986 standard defines quality as "the totality of features and characteristics of a product or service that bears its ability to satisfy stated or implied needs." In the context of manufacturing, quality is defined as strict and consistent adherence to measurable and verifiable standards to achieve uniformity of output that satisfies specific customer or user requirements. Quality can be determined objectively using criteria that are measurable, and subjectively which may be characteristics that can be observed and may be approximated, but cannot be measured. As a result, quality is a general term that refers to the desirable characteristics of material things and can mean different things to different people.

How is Quality Determined in Feed Ingredients and Feeds?

Feed manufacturers and animal producers use a variety of qualitative and quantitative methods to assess the quality of feed ingredients and feeds including physical, chemical and biological tests. Physical evaluation of feeds is qualitative but used to identify changes in the nature of the raw materials and feeds. The physical characteristics commonly evaluated include color, particle size, bulk density, homogeneity, smell, taste, touch and sound. The presence of other grains, weed seeds, husks and sand are the most common physical contaminants that can be identified by physical evaluation.

Chemical tests are quantitative and allow precise estimation of nutrient content and possible contaminants. Using a commercial laboratory to determine the proximate analysis of feed ingredients is a common practice to evaluate quality. These measurements typically include moisture, crude protein, crude fiber, crude fat and ash. Ingredient specifications (nutrient content) are essential for feed manufacturing quality assurance programs and serve as the basis for writing purchasing agreements, assessing quality, and to some extent, formulating diets. These nutrient specifications are the standards to which the delivered ingredient must conform to expectations and sometimes include measuring some potential contaminants of concern (e.g. mycotoxins, dioxin).

Feed microscopy is also used in determining if feeds or feed ingredients have been adulterated or contain contaminants. It involves examining samples of feed ingredients with a microscope under low (8x to 50x) and high (100x to 500x) magnification to evaluate shape, color, particle size, softness, hardness and texture of feeds.

Biological evaluation of feed ingredients is also done, but is generally confined to universities or large feed companies with animal and laboratory research facilities. It involves the use of animals, and personnel with specialized training to conduct digestion and metabolism trials on various animal species. These methods are time consuming, expensive and, as a result, cannot be routine procedures used as part of a feed manufacturing quality control program. However, they provide the best assessment of feed ingredient quality and feeding value compared to all other methods.

Thus, quality is a general term that refers to the desirable characteristics of material things and can mean different things to different people. For some, DDGS quality may refer to the absence of mycotoxins, and other undesirable anti-nutritional factors that may be detrimental to animal health and performance. To others, it may refer to consistency of nutrient content and digestibility. By these definitions, color can be, and is, used in some markets to define DDGS quality.

Why is Color Measured?

Color has been used as a subjective indicator of the nutritional quality of feed ingredients for decades. Free amino acids (especially lysine) can undergo Maillard reactions by combining with reducing sugars, rendering them indigestible by the animal. Louis Camille Maillard discovered and described the first evidence of these chemical reactions between sugars and amino acids in 1912. Maillard reactions are a group of chemical reactions that occur when heating sugars and amino acids, as well as complex carbohydrates and amides. These reactions commonly occur when mid- to high-protein feed ingredients are overheated during the production and drying process, and can be characterized by darkening of color (browning), burned flavor and burned smell. Drying temperatures used in dry-grind ethanol plants can range from 127 to 621° C. The nutritional significance of the Maillard reactions in DDGS has been shown in ruminants (Klopfenstein and Britton, 1987), as well as in pigs and chickens (Cromwell et al., 1993) and is responsible for losses in protein quality in DDGS (Cromwell et al., 1993; Fastinger and Mahan 2006; Stein et al., 2006). The Maillard reactions also occur in other common ingredients such as dried whey, blood meal and soybean meal. A darkening of color of these ingredients also indicates overheating and reduced protein quality. Therefore, feed ingredient purchasers and feed manufacturers have been trained to use color as a general indicator for differentiating protein quality and digestibility among feed ingredient sources.

In addition, color can give an indication of the maturity of the grain, storage conditions, presence of toxins, contamination due to sand and possible use of insecticides/fungicides, which give a dull and dusty appearance. Sorghum with an orange to red color may indicate high tannin content. Browning or blackening of grain or grain co-products can indicate excessive heat treatment or spoilage due to improper storage, thus reducing nutritive value. Black colored fish meal may indicate rancidity of fish oil.

How is Color Measured?

Hunter and Minolta colorimeters have been used for many years in human food industry as indicators of nutritional and physical characteristics of heat-processed products such as candy bars, cookies and bread. In these food products, color is often an important quality attribute that determines the attractiveness of the product to consumers. Color is measured by reading three color characteristics specifically defined by the Commission Internationale d'Eclairage, in Vienna, Austria. [Lightness or L* (0 dark, 100 lighter), a* (redness-greenness) and b* (yellowness-blueness); Figure 2]. Colorimetric measurements of feed ingredients, especially for DDGS, have become common in the feed industry to assess the extent of heat damage of mid- to high-protein ingredients. It is important to realize color scores using Minolta colorimeters are lower than for Hunter Lab colorimeters. Urriola et al. (2013) showed that L* readings are generally 2.9 units lower and b* readings are 1.7 units lower for Minolta compared to Hunter readings of the same sample. However, the ranking of samples by color scores using both methods is the same. Therefore, if color measures are used as criteria for marketing DDGS sources, it is essential the method used (e.g. Hunter or Minolta) is defined in the contract to avoid misinterpretation of results.

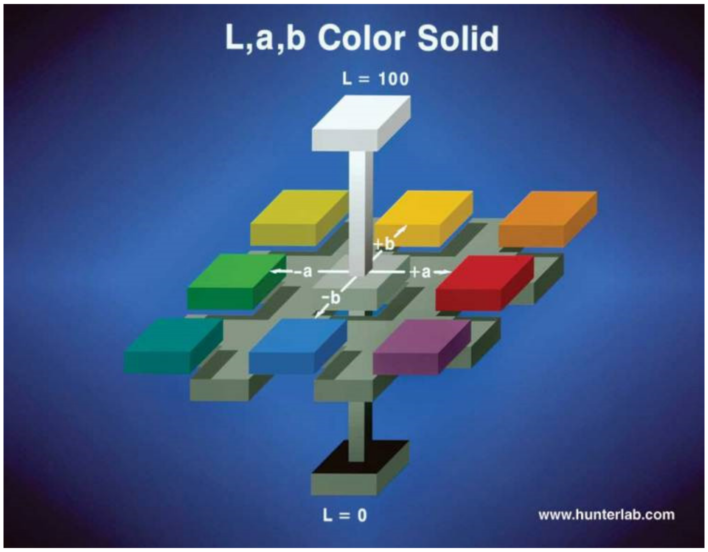

Figure 2. Hunterlab color measurement scales

Why is Color Important in Some Export Markets?

When living and working in a global economy, it is essential to understand how different cultures around the world perceive things, the symbolic nature of how they may think and the basis for the actions they choose to take. As an example, the web site (http://webdesign.about.com/od/colorcharts/l/bl_colorculture.htm) describes what different colors mean in different cultures. For example, the color yellow in Chinese culture is considered the most beautiful and corresponds with earth and the center of everything (http://en.wikipedia.org/wiki/Color_in_Chinese_culture). Yellow is ranked above brown and also signifies neutrality and good luck. Yellow was the color of Imperial China, is the symbolic color of the five legendary emperors of ancient China, often decorates royal palaces, altars and temples and was used in the robes and attire of the emperors. Yellow also represents freedom from worldly cares and is highly regarded in Buddhism.

Furthermore, consumers in many Asian countries prefer dark yellow-colored egg yolks and yellow-colored chicken skin over pale colored egg yolks and chicken skin typical of that found in the U.S. Therefore, the color yellow or golden is held in higher esteem than brown and is likely one of the contributing factors to why "golden" DDGS is the preferred color of DDGS in many parts of Asia.

Is There a Relationship Between DDGS Color and Nutritional Value?

Variation in color among DDGS sources

There are significant differences in color among U.S. corn DDGS sources (Figure 3). Fifteen studies have been conducted to evaluate the range of color (L*, a* and b*), or degree of heating, among DDGS sources and its relationship to differences in nutritional quality and physical characteristics. A summary of the key findings of these studies is shown in Table 1. All but two studies (Urriola et al, 2013; Song and Shurson, 2013) evaluated DDGS samples from a limited number of sources (two to nine sources). However, despite the limited number of sources evaluated in most of these studies, there was a significant range in L* color scores among the samples analyzed except for the studies reported by Rosentrater (2006), Pahm et al. (2009), and Kingsly et al. (2010). Samples of DDGS from beverage ethanol plants were included in the Cromwell et al. (1993) and Urriola et al. (2013) studies, which may be the reason for the extremely low L* values (dark samples) in those studies, but does not explain the low L* values obtained in the studies by Fastinger and Mahan (2006) and Bhadra et al. (2007), when only DDGS from fuel ethanol plants were evaluated.

Figure 3. Color differences among U.S. corn DDGS sources

Table 1. Summary of research results involving DDGS color (or degree of heating) on nutritional and physical characteristics

Reference	# DDGS sources	L* range	a* range	b* range	Key findings
Cromwell et al. (1993)	9	28.9-53.2	ND	12.4-24.1	Significant correlation between DDGS L* and lysine level and L* and b* with weight gain and gain:feed in broiler chicks. Effects were similar in pigs. ADIN of DDGS sources was also highly correlated with chick weight gain and gain:feed.
Whitney et al. (2001)	2	ND; Light and Dark	ND	ND	Lighter colored DDGS had an AID for lysine of 47.4 percent but darker colored DDGS had an AID for lysine of 0 percent for pigs.
Ergul et al. (2003)	4	41.8-53.8	ND	32.9-42.8	Significant correlations between L* and b* and digestible lysine in poultry.
Roberson et al.(2005)	2	ND; Light and Dark	ND	ND	Light-colored source had 29.8 mg/kg xanthophyll, dark-colored source had 3.5 mg/kg xanthophylls
Rosentrater (2006)	6	40.0-49.8	8.0-9.8	18.2-23.5	L*, a* and b* were correlated with several physical properties
Batal and Dale (2006)	6	47.9-62.9	4.1-7.6	8.8-28.4	Significant correlations were found between digestible Lys, Thr, Arg, His and Trp and L* values and b* values, but not with a* values.
Fastinger and Mahan (2006)	5	28.0-55.1	6.7-9.0	15.8-41.9	DDGS sources with higher L* and b* color had greater apparent and standardized digestibility of AA in pigs than DDGS sources of a darker color.
Urriola (2013)	34	36.5-62.5	8.0-12.0	21.3-47.0	Digestible crude protein and amino acids were poorly predicted (R2 less than 0.30) from Minolta or Hunter color scores in pigs. Correlation (R2 =0.48) between L* and SID lysine was higher among samples with L* less than 50 than samples with L* greater than 50 (R2 =0.03).
Bhadra et al. (2007)	3	36.6-50.2	5.2-10.8	12.5-23.4	Color parameters a* and b* had high correlations with water activity and moderate correlations with thermal properties which may be important for feed storage and further processing
Martinez Amezcua and Parsons(2007)	ND	ND; heat process-sed light colored DDGSsample	ND	ND	Increased heating of DDGS significantly increased relative phosphorus bioavailability in DDGS in poultry, but amino acid digestibility, especially lysine, was greatly reduced.
Ganesan et al. (2008)	ND	40.8-54.1	12.4-18.7	57.6-73.3	Amount of solubles added to grains to make DDGS reduced L* and increased a* and interacts with moisture content to affect DDGS color.
Liu (2008)	6	44.9-59.6	8.3-11.4	31.0-46.4	Most DDGS samples showed a decrease in L* and b* and a slight increase in a* as particle size increased.
Pahm (2009)	7	49.3-56.4	10.4-14.5	36.7-43.9	Correlation between L* and SID lysine in chicks was poor (0.29), but very high (0.90) for relative bioavailability of lysine.
Kingsly et al. (2010)	1	49.0-53.4	8.8-11.3	24.7-26.5	As the CDS level was reduced, L* value increased and a* decreased.
Song et al. (2013)	31	45.2-58.1	9.3-12.4	26.6-42.4	Significant correlations between measures of fat oxidation (TBARS and PV) and L* and b*. DDGS TBARS were 5 to 25x greater than corn.

ND = not measured

Is Color Related to Lysine Digestibility in DDGS?

Research by Evans and Butts (1948) was the first to show that excessive heating of feed ingredients can result in binding of amino acids and protein to other compounds, such as fiber, and reduce amino acid digestibility (especially lysine) in monogastric animals (i.e. swine, poultry, fish). As a result, the use of color as an indicator of excessive heating and reduced amino acid digestibility in DDGS, has been a primary objective in seven of the 15 research studies conducted (Table 1). The first evidence of the relationship between DDGS color, lysine content, and animal performance was published by Cromwell et al. (1993). They showed that lysine concentrations tended to be highest in the lightest colored DDGS sources, intermediate in the medium colored, and lowest in the darkest-colored DDGS sources. In addition, there was a significant correlation between Hunter L* and weight gain and gain:feed in broiler chicks. When DDGS sources of similar color scores were blended and fed to pigs, performance results were similar to those observed in the chick studies. Additional poultry studies by Ergul et al. (2003) and Batal and Dale (2006) evaluated DDGS sources representing a wide range of L* and b* values and confirmed the results by Cromwell et al. (1993) by showing that L* and b* were significantly correlated with digestibility of lysine and other amino acids. However, results from a recent study by Pahm et al. (2009), which evaluated seven DDGS sources that could be classified as "golden" in color, and had a narrow range in L* values (49 to 56), showed no effect of L* on lysine digestibility in poultry, but there were significant differences in the relative bioavailability of lysine among these sources.

Similarly, results from additional pig studies (Whitney et al., 2001; Fastinger and Mahan, 2006) showed lower amino acid digestibility in DDGS sources that had lower L* values (darker in color) compared with sources with higher L* values. However, Urriola et al. (2013) was the first to demonstrate using a large number of DDGS samples (n = 34) over a wide range of L* values (37 to 63) that digestible crude protein and amino acids were poorly predicted (R2 less than 0.30) from Minolta or Hunter color scores in pigs. The association between L* and digestible lysine was greater for samples with an L* less than 50 compared to samples with L* greater than 50 (Figure 4). However, even for DDGS samples with L* less than 50, the correlation between L* and digestible lysine content in pigs was relatively low (R2 = 0.48), indicating color cannot be used to accurately predict digestible lysine content among DDGS sources. The results from these studies indicate that L* and b*, but not a* may be useful general indicators of relative lysine digestibility if L* values are less than 50, but not if L* values are greater than 50.

Relationship Between DDGS Drying Temperature and Relative Phosphorus Bioavailability

Although, there is consistent evidence that excessive heating (lower L* and dark color) during DDGS drying reduces digestibility of lysine and other amino acids, it may increase the relative bioavailability of phosphorus for poultry. Martinez-Amezcua and Parsons (2007) applied increasing heating temperatures to light-colored DDGS samples and observed that the relative bioavailability of phosphorus was improved, but amino acid digestibility was greatly reduced. This is the first evidence demonstrating excessive heating of DDGS may enhance its nutritional value for poultry by improving the utilization of phosphorus.

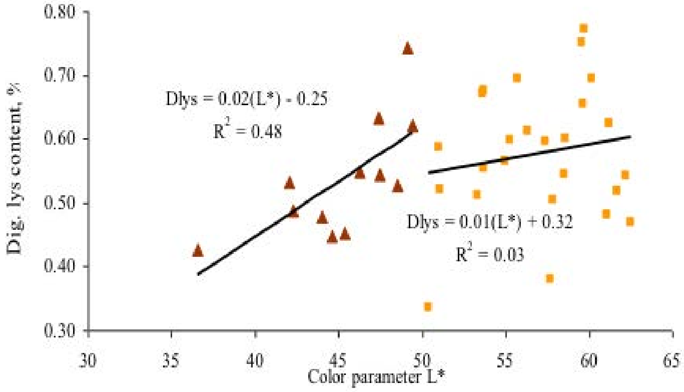

Figure 4. Relationship between lightness of color (L*) and digestible lysine content of corn DDGS for swine. (Urriola et al., 2013)

Relationship Between DDGS Color and Xanthophyll Content

Limited studies have been conducted to determine xanthophyll content in DDGS. Xanthophylls are yellow/orange pigments naturally occurring in corn and corn co-products, and are valuable components in poultry diets in many countries, especially Asia, to produce a desired golden color in egg yolks and broiler skin. Synthetic xanthophyll pigments (often derived from marigold petals) are very expensive, but are commonly added to poultry diets in Asian countries as the primary source of pigment. Therefore, adding corn co-products such as corn gluten meal, and to a lesser extent, DDGS, to poultry diets reduces the need for using expensive synthetic pigments and consequently, reduces diet cost while meeting desired egg yolk and skin color quality standards preferred by consumers.

Xanthophyll values in DDGS have been reported to be between 10.6 mg/kg and 34.0 mg/kg (Sauvant and Tran, 2004). Roberson et al. (2005) did not use Minolta or Hunter colorimeters to measure color, but showed that dark-colored DDGS contained 3.5 mg/kg xanthophyll compared to light golden colored DDGS which contained 29.8 mg/kg xanthophyll. They indicated that overheating of DDGS may cause oxidation of xanthophyll resulting in lower concentrations. Therefore, it appears that lighter colored DDGS is more likely to contain higher amounts of xanthophylls than darker colored DDGS.

Relationship Between DDGS Color and Lipid Peroxidation

Limited research has been conducted to evaluate the extent of oil peroxidation in corn DDGS. Dried distillers grains with solubles contains five to 13 percent corn oil, and corn oil contains high concentrations of polyunsaturated fatty acids (particularly linoleic acid) susceptible to lipid peroxidation. Drying temperatures used by ethanol plants can vary substantially (85 to 600°C), and increased drying time and temperature used during the drying process accelerates lipid peroxidation. Feeding diets containing peroxidized lipids have been shown to negatively affect pig and broiler health and growth performance (L'Estrange et al.,1967; Dibner et al., 1996; DeRouchey et al., 2004; Hung et al., 2017). Harrell et al. (2010) showed that feeding peroxidized corn oil or DDGS to nursery pigs resulted in reduced growth performance compared with pigs fed fresh (non-peroxidized) corn oil. Song and Shurson (2013) determined the thiobarbituric acid reactive substances (TBARS) and peroxide value (PV), which are common analytical methods to measure lipid peroxidation, in 31 corn DDGS, and reported that TBARS content ranged from 1.0 to 5.2 ng MDA equivalents/mg oil, and PV ranged from 4.2 to 84.1 meq/kg oil. The DDGS sample with the highest TBARS and PV values was 25 and 27 times greater, respectively, than the concentrations found in corn. These authors also reported there was a significant negative correlation between L* and b* and the level of lipid peroxidation among DDGS sources. These results indicate that darker and less yellow DDGS source may have greater concentration of peroxidized compounds than lighter colored DDGS sources.

Is There a Relationship Between DDGS Color and Physical Characteristics?

Five experiments (Table 1) have been conducted to understand the relationship between DDGS color and its physical characteristics, which may affect storage and further feed processing. Rosentrater (2006) was the first to report that L*, a* and b* were correlated with several physical properties (moisture, water activity, conductivity, resistivity, bulk density and flowability) of DDGS. Bhadra et al. (2007) confirmed these findings and showed a* and b* had high correlations with water activity and moderate correlations with thermal properties of DDGS indicating color may be an indicator for assessing feed storage and further processing characteristics.

Variable amounts of condensed distiller's solubles are added to the coarse grains fraction to produce DDGS among ethanol plants. The proportion of solubles and coarse grains used to produce DDGS affects the nutrient composition of DDGS because the nutrient content of each of these fractions is substantially different. The coarse grains fraction is higher in dry matter (33.8 vs. 19.5 percent), crude protein (33.8 vs. 19.5 percent), and crude fiber (9.1 vs. 1.4 percent), but lower in crude fat (7.7 vs. 17.4 percent), ash (3.0 vs. 8.4 percent), and phosphorus (0.6 vs. 1.3 percent) than the condensed solubles fraction. Therefore, increasing proportions of condensed solubles added to the coarse grains fraction will increase crude fat, ash and phosphorus but reduce crude protein and crude fiber content of DDGS.

Noll et al. (2006) evaluated the nutrient composition and digestibility of batches of corn DDGS produced with varying levels of solubles added to the wet grains. The DDGS samples produced contained solubles added at approximately 0, 30, 60 and 100 percent of the maximum possible addition of solubles to the grains. This corresponds to adding 0, 12, 25 and 42 gallons of syrup to the grains fraction per minute. Dryer temperatures decreased as the rate of solubles addition to the grains decreased. Particle size increased, and was more variable, as increasing additions of solubles were added to the grains fraction. Adding increasing amounts of solubles resulted in darker colored DDGS (reduced L*) and less yellow color (reduced b*) (Table 2). Increased addition of solubles resulted in increased crude fat, ash, TMEn (poultry), magnesium, sodium, phosphorus, potassium, chloride and sulfur, but had minimal effects on crude protein and amino acid content and digestibility. Ganesan et al. (2008) and Kingsly et al. (2010) demonstrated that as the amount of condensed distillers solubles added to the coarse grains fraction is increased, L* is reduced and a* increases. Therefore, DDGS L* and a* can be general indicators of nutrient composition changes among DDGS samples.

University of Minnesota research has shown there is considerable variation (256 to 1,217 µm) in particle size among DDGS sources, and DDGS particle size can affect digestible energy (DE) and metabolizable energy (ME) content for swine (Liu et al., 2012). Liu (2008) reported most DDGS samples showed a decrease in L* value and b*, and a slight increase in a* value as DDGS particle size increased.

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

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

Adapted from Noll et al. (2006).

Is Color the Best Indicator of DDGS Quality?

No. As previously discussed, there are many factors that affect the color of DDGS and some of these factors have positive effects while others have negative effects on nutritional value of DDGS It is also important to remember there are many criteria that can be used to describe DDGS "quality." Color is correlated with several nutritional components and physical characteristics of DDGS. While many nutritionists perceive that dark-colored DDGS is an indication of low lysine digestibility, the association of color over a broad range of L* values (36 to 64) with lysine digestibility indicates it is a poor predictor. Furthermore, DDGS sources with a high L* may indicate greater xanthophyll content, and minimal lipid peroxidation. In contrast, darker colored DDGS sources may have higher concentrations for some nutrients compared to lighter colored DDGS sources. For example, adding increasing levels of solubles to the coarse grains fraction when producing DDGS sources increases the energy, crude fat and mineral content, with minimal effects on crude protein and amino acid content and digestibility, compared to lighter colored DDGS sources containing less solubles. Furthermore, darker colored samples appear to have higher relative phosphorus bioavailability for poultry. Particle size, moisture content and other physical properties of DDGS are also correlated with color, but the value of these relationships is more difficult to assess from a feed manufacturing and nutritional perspective. Therefore, using color as an indicator of DDGS quality is not recommended.

How Should DDGS Quality Be Determined?

For most DDGS users, a high-quality DDGS source is one is high in energy and nutrient content and digestibility, and free of anti-nutritional factors such as mycotoxins. Energy, followed by protein (amino acids) and phosphorus are the three most expensive nutritional components in animal feeds. Therefore, accurate methods for determining the metabolizable energy, digestible amino acids and digestible or available phosphorus among various DDGS sources must be used. To do this, accurate ME and digestible amino acid prediction equations have been developed, validated and published for swine and poultry. For more information about these prediction equations, see Chapters 19 and 22 in this handbook. Unfortunately, accurate prediction equations have not been developed for estimating digestible or available phosphorus in DDGS for swine and poultry, nor have prediction equations been developed to estimate net energy, rumen degradable and undegradable protein of DDGS sources for ruminants. Recommended methods for determining mycotoxin content in DDGS are discussed in Chapter 8 of this handbook.

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CHAPTER 11

Feed Safety of DDGS

Introduction

FEED SAFETY HAS A SIGNIFICANT IMPACT ON OUR GLOBAL FOOD SAFETY SYSTEM because it not only directly affects animal health and productivity, but it also affects the safety of animal-derived food products for human consumption. Feed contamination can affect the entire food chain and costs millions of dollars in lost revenue and increased costs. Furthermore, it creates fear and panic among consumers, reduces the amount of food available for consumption and reduces consumer trust in the food system. Illness, death and potential future health risks can also occur. As a result, feed safety is directly linked to food safety and had led to the concept of "feed is food."

We live and work in a global economy, with feed ingredients and food products imported and exported in all countries. However, feed and food safety standards and regulations vary dramatically among countries. Feed and feed ingredients can potentially be contaminated with undesirable microbiological, physical and chemical hazards, and because of the increasing interconnectivity of global supply chains, one feed contamination event can have widespread effects on animals and food. Therefore, as the global marketing, production and distribution of feed and food continues to increase, the potential risks of acquiring undesirable feed contaminants also increases (Liu, 2011). In fact, the increased need for transparency of origin of some feed ingredients has led to the development of analytical technologies to authenticate and differentiate botanical and geographical origin of grains and co-products in the international feed market (Tres et al., 2014; Tena et al., 2015).

It is essential for feed ingredient suppliers, buyers and feed manufacturers to not only be in compliance with local government regulatory agencies, but also develop and implement programs for continuous quality and safety improvements in all aspects of the feed and food chain. Many progressive feed and animal production companies in over 150 countries have implemented ISO (International Organization for Standardization) standards to more efficiently and safely produce products which ultimately lead to more standardized products for consumers. Companies that implement ISO standards must document standards and ensure compliance through internal audits, while also verifying compliance through external audits with the goal of becoming certified. In addition, progressive feed manufacturers have also implemented HAACP (Hazard Analysis and Critical Control Point) systems which are designed to prevent feed and food contamination events along every step of the manufacturing, storage and distribution segments of the feed and food supply chains. There are seven principles in developing and implementing a HAACP plan including:

1. Conduct a hazard analysis
2. Identify critical control points
3. Establish minimum and maximum limits of the manufacturing process to control potential hazards
4. Establish critical limits
5. Establish monitoring procedures and corrective actions
6. Establish record-keeping procedures
7. Establish verification procedures

Food safety management systems must be designed to manage quality and provide continual improvement within feed companies by combining ISO 9001 and HAACP principles to decrease this risk of food-borne pathogens, emerging new pathogens and protect branded products by controlling risk.

Implementation and monitoring of feed and food safety systems are continually improving in many countries. In fact, the U.S. has recently adopted even more rigorous feed safety regulations (including DDGS production) to further minimize the risk of food safety hazards for consumers. In January, 2012, the Food Safety Modernization Act was signed into law in the U.S., and was the first significant update and expansion of the U.S. Food and Drug Administration's (FDA) food and feed safety regulatory powers in nearly 70 years (Brew and Toeniskoetter, 2012). Although feed production facilities (including ethanol plants) in the U.S. have been required to be registered with the FDA since 2002, this new law provides the FDA greater authority to revoke a facility's registration due to food or feed safety reasons. This law also prohibits shipping food or feed by interstate commerce without a current registration. As a result, the FDA can force termination of sales, and even order a mandatory recall, if it finds significant food or feed safety violations. The implementation of this new law requires ethanol plants to develop and implement a Hazard Analysis and Critical Control Point (HACCP) plan for the co-products they produce. This law requires feed manufacturers to evaluate known or potential feed safety hazards, identify and implement preventative control procedures, monitor those procedures, take corrective actions when they are not working and periodically verify the overall system is working effectively. There is also a requirement of written documentation of these feed safety production procedures, and ethanol plants are inspected by the FDA for compliance. Enactment of this new law will provide even greater assurance and confidence that U.S. DDGS will meet the most strict feed safety requirements in the world.

In addition to new regulations and compliance with the Food Safety Modernization Act regulations, some U.S. ethanol plants are also implementing GMP (Good Manufacturing Practices)+ Feed Certification to meet strict feed safety standards for co-products in many countries and markets. The GMP+ Feed Certification Scheme was first developed in 1992 by the feed industry in the Netherlands in responses to various events involving contamination of feed ingredients. Today, GMP+ Feed Certification has expanded to become an international program managed by GMP+ International in collaboration with numerous international stakeholders. In 2013, the GMP+ program was further expanded to now include GMP+ Feed Safety Assurance and GMP+ Feed Responsibility Assurance. Implementation of GMP+ Feed Safety Assurance by ethanol plants is becoming necessary as a "license to sell" DDGS to progressive integrated feed and animal production companies in many countries and markets by complying with standards for the assurance of feed safety throughout all segments of the feed supply chain. Furthermore, there are increasing demands for the global animal feed industry to operate in a more responsible manner by sourcing feed ingredients that minimize effects on competing with food security for humans (e.g. soybeans and fishmeal) and the minimizing negative impacts on the environment.

Fortunately, the risk of hazardous microbial, physical and chemical contaminants in U.S. DDGS is extremely low. Corn and corn DDGS have no antinutritional factors except phytate indigestible form of phosphorus), which is found in various concentrations in all grains and grain-based co-products. However, widespread commercial availability and use of phytases have been shown to be cost effective for degrading phytate and improving phosphorus digestibility of grain-based diets for monogastric animals.

The focus of this chapter to provide a brief overview of potential feed safety microbiological, chemical and physical risk factors in DDGS that need to be considered when feeding DDGS to various food animal species. The primary potential contaminants of concern are pathogenic microorganisms, mycotoxins, antibiotic residues and sulfur, and readers are encouraged to refer to Chapter 13 (Antibiotic Use in DDGS Production), Chapter 14 (Mycotoxins in DDGS), Chapter 15 (Benefits and Concerns of Sulfur in DDGS), and Chapter 19 (DDGS and E. coli O157:H7 Shedding in Beef Cattle) for more detailed information on these topics.

Potential Microbiological Risk Factors

Corona virus transmission in feed and feed ingredients

Corona viruses (transmissible gastroenteritis virus – TGEV; porcine delta corona virus – PDCoV; porcine epidemic diarrhea virus - PEDV) have had devastating effects in the global pork industry. These viruses are excreted in feces; can be transmitted by contaminated equipment, personnel and other fomites; cause severe diarrhea, high mortality, subsequent reductions in growth performance and reduce profitability. The Porcine Epidemic Diarrhea virus (PEDV) had devastating effects on pig mortality in the U.S. in 2013, and feed and feed ingredients were identified as significant risk factors for its transmission. As a result, research was conducted to determine corona virus survival in feed and feed ingredients and potential mitigation strategies to minimize their transmission through feed to pigs. Dee et al. (2015) showed that PEDV survival in feed varies among types of ingredients and appears to survive the longest in soybean meal, but applying a formaldehyde-based liquid treatment caused virus inactivation in all ingredients. Similarly, Trudeau et al. (2017) evaluated survival of PEDV, TGEV and PDCoV in various feed ingredients, including DDGS sources with variable oil content (Figure 1). The PED virus survived the longest, and TGEV and PDCoV also had high survival in soybean meal compared to several all other ingredients. Interestingly, virus survival was very low in the low- and high-oil DDGS sources (1.0 and 0.8 days for TGEV and 0.7 to 0.6 days for PEDV, respectively), compared with the medium-oil DDGS source (1.7 days for TGEV and 7.3 days for PEDV). In contrast, PDCoV survived longer in the low- and high-oil DDGS sources, compared with medium-oil DDGS, blood meal, complete feed, meat meal and spray dried plasma. Survival time of all viruses was much less in DDGS sources than in soybean meal, and survival of TGEV and PDCoV in DDGS was much less compared with corn. These results suggest soybean meal is a greater risk factor for transmission of corona viruses via feed than DDGS and other common feed ingredients. Unfortunately, no studies have been conducted to determine if other pathogens, such as avian influenza virus, can be transmitted through feeding ingredients, or their potential survival in feed ingredients during transport and storage.

Salmonella transmission in feed and feed ingredients

No data are available, nor are there government regulations related to controlling potential Salmonella contamination of DDGS. There has been a long-term scientific debate regarding the feasibility and likely efficacy of enforcing a Salmonella negative standard for animal feeds to reduce the incidence of human salmonellosis (Davies et al., 2004). It is difficult to assess the impact of reducing Salmonella contamination in animal feeds on the risk of human foodborne salmonellosis. Factors that may reduce or eliminate the potential benefit of regulatory interventions in commercial feed include:

- Widespread use of on-farm feed mixing
- Incomplete decontamination of feed during processing
- Post-processing feed contamination at the feed mill
- Contamination during feed transport or on-farm storage
- Numerous non-feed sources of Salmonella
- High risk of post-farm infection in lairage
- Post-harvest sources of Salmonella contamination

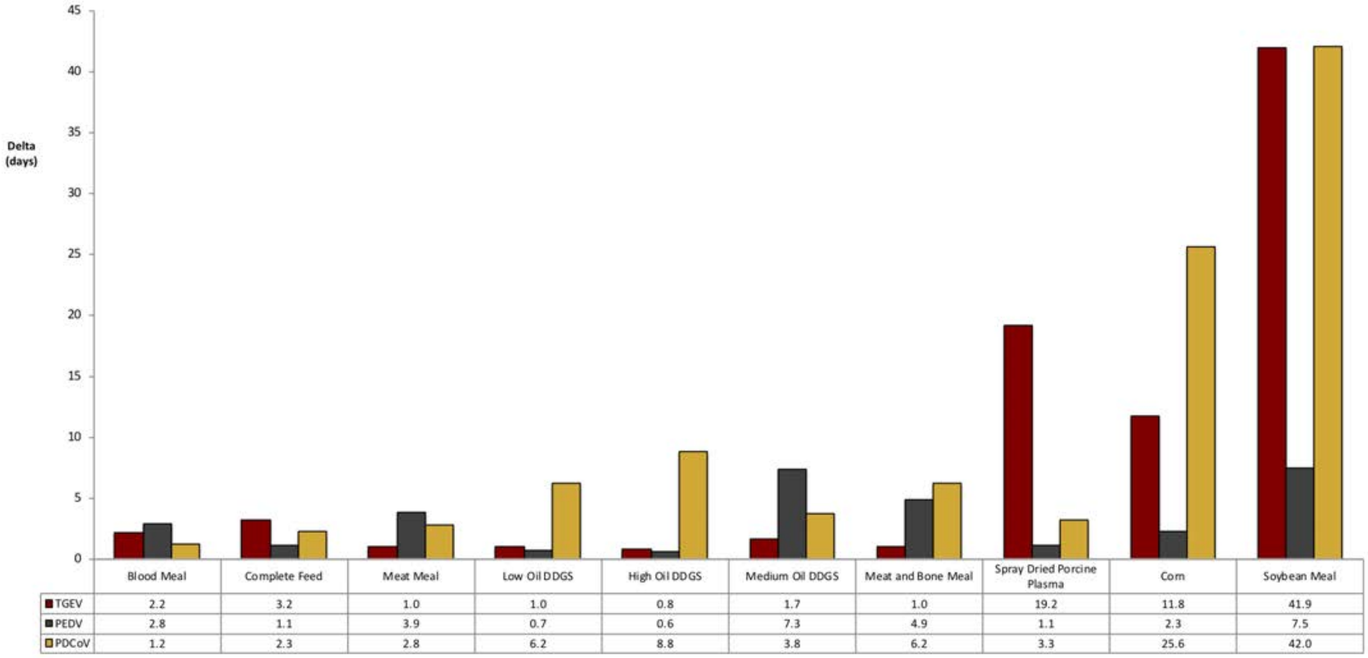
Potential risk of Salmonella, Escherichia coli O157:H7 and Clostridium perfringens shedding when feeding DDGS diets

The gastrointestinal tracts of animals naturally contain E. coli O157:H7 and Salmonella, which are foodborne pathogens and can be shed in feces leading to potential contamination of food products and cause illness to consumers. A series of studies have been conducted by one research group (Jacob et al., 2008a,b,c) that showed an inconsistent but generally low prevalence of E. coli O157:H7 shedding when DDGS was fed to beef cattle. Other studies (Peterson et al., 2007; Nagaraja et al., 2008) have also shown that E. coli shedding occurs in beef cattle, but feeding high dietary levels of DDGS did not influence pathogen shedding. Furthermore, there was no association between feeding DDGS or dry-rolled corn diets on E. coli O157:H7 or Salmonella prevalence (Jacob et al., 2009). These results indicate there is minimal risk of increased shedding of E. coli O157:H7 or Salmonella from feeding DDGS to cattle.

Further studies in growing-finishing pigs have shown no effect on the susceptibility or colonization of Salmonella typhimurium when feeding DDGS diets (Rostagno et al., 2013). In broilers, Loar et al. (2010) showed feeding DDGS diets had no effect on Clostridium perfringens and Escherichia coli counts in cecum contents of broilers. These results indicate there appears to be minimal risk, if any, that feeding DDGS to beef cattle, swine and broilers is associated with increased risk of transmission of food-borne pathogens to meat products.

Mycotoxins

Of all feed safety risk factors for DDGS, the potential for mycotoxin contamination is perhaps the greatest concern. Mycotoxins are produced by fungi during the growing season and under specific environmental conditions during storage. From a human food safety perspective, aflatoxins are the only class of mycotoxins regulated by the U.S. FDA because of it's carcinogenic effects. However, if feed ingredients contain high dietary concentrations of various mycotoxins, detrimental effects on nutrient utilization, immune function and several other adverse physiological effects can occur that lead to reduced animal health and performance. Swine and poultry are generally more susceptible to mycotoxins than ruminants, and young animals are more susceptible than older animals in each species. Although mycotoxins are produced by specific fungi strains, measuring mold counts in feed ingredients are worthless because these analyses provide no information or confirmation regarding the potential presence or concentrations of mycotoxins.



	Blood Meal	Complete Feed	Meat Meal	Low Oil DDGS	High Oil DDGS	Medium Oil DDGS	Meat and Bone Meal	Spray Dried Porcine Plasma	Com	Soybean Meal
■ TGEV	2.2	3.2	1.0	1.0	0.8	1.7	1.0	19.2	11.8	41.9
■ PEDV	2.8	1.1	3.9	0.7	0.6	7.3	4.9	1.1	2.3	7.5
■ PDCoV	1.2	2.3	2.8	6.2	8.8	3.8	6.2	3.3	25.6	42.0

Figure 1. Corona virus (transmissible gastroenteritis – TGEV, porcine epidemic diarrhea – PEDV, porcine delta cornona virus (PDCoV) survival in complete feed and common feed ingredients (Trudeau et al., 2017)

The prevalence and concentrations of mycotoxins in corn, other grains and DDGS vary among countries around the world (Biomin, 2014). Studies have shown that the prevalence of mycotoxin contamination and concentrations in DDGS produced in the USA are much lower compared with feed ingredients produced in China (Biomin, 2014; Guan et al., 2011; Li et al., 2014). Two extensive surveys of mycotoxin contamination in DDGS produced in the USA have been published (Zhang et al., 2009; Khatibi et al., 2014) that show relatively low concentrations of various mycotoxins in DDGS relative to existing guidelines. Zhang et al. (2009) analyzed a total of 235 DDGS samples from 20 ethanol plants in the U.S., as well as 23 DDGS samples collected from 23 export shipping containers from 2006 to 2008, and reported that:

1. None of the DDGS samples contained aflatoxins or deoxynivalenol concentrations above the U.S. FDA guidelines for use in animal feed.

2. None of the DDGS samples had fumonisins concentrations greater than FDA guidelines for use in dairy, beef, swine, poultry and aquaculture feeds, and only 10 percent of the samples contained concentrations of fumonisins greater than maximum recommend concentrations for use in horse and rabbit feed (which are the most sensitive species to fumonisins).

3. None of the samples contained detectable concentrations of T-2 toxins, and most samples contained undetectable concentrations of zearalenone.

4. Use of containers to export DDGS did not lead to increased mycotoxin production.

More recently, Khatibi et al. (2014) conducted a DDGS mycotoxin survey where they collected and analyzed 141 corn DDGS samples, from 78 ethanol plants located in 12 states in the U.S., for the presence and concentrations of various tricothecenes. There was an unusually high prevalence of Fusarium spp. molds in corn produced in the USA in 2011, which was a result of adverse weather conditions during the corn growing season. In this extreme case, 69 percent of the samples contained no detectable levels of deoxynivalenol, only 5 percent of the samples were above the FDA advisory levels for swine, and only 19 percent of the samples contained detectable concentrations of zearalenone.

Results from these studies indicate mycotoxins can be present in corn DDGS, but the prevalence and concentrations of DDGS produced in the U.S. are much lower than DDGS produced in China. Therefore, depending on geographic origin and the prevalence of mycotoxins in corn during a given year, high diet inclusion rates of DDGS can be used if the prevalence and concentrations of mycotoxins are low to minimize the risk of exceeding total diet mycotoxin concentrations above recommended levels.

Potential Chemical Risk Factors

Antibiotic residues

A few types of antibiotics are often added in small amounts to fermenters to control bacterial infections during starch fermentation to produce ethanol and co-products. The U.S. FDA has not restricted the use of antibiotics in ethanol production, and the predominant one used (virginiamycin) has been reviewed by expert scientific panels and deemed Generally Recognized as Safe. The global use of antibiotics for growth-promoting purposes has been eliminated in the U.S. and E.U., with other countries also decreasing their use in food animal production. The primary concerns related to antibiotic use are the potential risks of residues in meat, milk and eggs and the development of antibiotic resistance in animals and humans. The U.S. FDA has conducted surveys to determine the prevalence and concentrations of several antibiotic residues in DDGS using a multi-residue detection method (de Alwis and Heller, 2010; Kaklamanos et al., 2013), but the results have not been published. Choice of analytical procedures is very important because the presence of some antibiotic residues (e.g. virginiamycin) can only be accurately quantified using bioassays.

Only one study has been conducted to determine the prevalence, concentrations and biological activity of antibiotic residues in 159 distillers co-product samples, collected quarterly from 43 ethanol plants in nine states in the U.S. (Paulus-Compart et al., 2013). The results from this study showed that 13 percent of the samples contained low (less than1.12 mg/kg) concentrations of antibiotic residues. When extracts of samples were tested for biological activity using selected sentinel bacteria, only one sample (which had no detectable concentrations of antibiotic residues) inhibited growth of Escherichia coli, and none of the samples inhibited Listeria monocytogenes growth. Therefore, the likelihood of detecting antibiotic residues in DDGS is very low, and if detected, there is minimal risk that residues have any residual biological activity. Since the time this study was conducted, there has been a significant decline in antibiotic use in ethanol production, which is attributed to improved sanitation and availability of other non-antibiotic additives to control bacterial infections during fermentation. In fact, some ethanol plants are now producing antibiotic-free DDGS.

Dioxins

No studies have been conducted to assess potential dioxin contamination in DDGS, nor are there any regulations. Dioxins are a group of chemicals representing over 210 different compounds and are ubiquitous to the environment. Only 17 of these compounds are of toxicological concern and are not produced intentionally. Therefore, they can't be simply prohibited. Dioxins are formed as a by-product of chemical processes, and are insoluble in water and soluble in lipids. Dioxins are not biodegradable and can accumulate in the food chain. Maximum dioxin concentration limits have been established for citrus pulp and kaolinitic clay, and fish oil and fish meal are the most common feed ingredients with dioxin contamination. Animal fats may also contain dioxins, but at low concentrations, while cereals and seeds, milk by-products and meat and bone meal are less commonly contaminated with dioxins.

Genetically modified corn (GM)

Unlike the U.S., several countries have concerns about the safety of genetically modified (GM) crops, and as a result, legally prohibit or restrict production or imports of some, if not all GMO grains and grain co-products. This restriction continues to be controversial, although there are limited supplies of feedstuffs for animal production in many countries around the world to provide adequate food security. In 2015, about 92 percent of all corn acres planted in the USA utilized genetically engineered varieties (USDA-NASS, 2015). Therefore, the majority of U.S. corn DDGS that is produced uses GM corn varieties.

More than 165 genetically engineered events in 19 plant species (including corn and soybeans) have been approved in the U.S. (James, 2013), and all were evaluated using a comprehensive safety risk assessment by the U.S. FDA. All of the genetically modified events evaluated by the U.S. FDA, as well as regulators in Japan, during the past 20 years have been shown to have equivalent safety compared with conventional crop varieties (Herman and Price, 2013). Furthermore, internationally accepted guidelines developed by the Codex Alimentarius Commission (www.codexalimentarius.org) are used for risk assessment of genetically modified organisms.

There is a substantial amount of scientific evidence that GMO crops are safe. The Council for Biotechnology Information has published a statement indicating that "The Food and Drug Administration (FDA) has determined that biotech foods and crops are as safe as their non-biotech counterparts. The American Medical Association, the American Dietetic Association, and the U.S. National Academy of Sciences have also declared biotech foods safe for human and animal consumption. In addition, since being introduced to U.S. markets in 1996, not a single person or animal has become sick from eating biotech foods. Other international groups that have concluded biotech foods and crops are safe are The United Nations Food and Agriculture Organization, the World Health Organization, the International Council for Science, the French Food Agency, and the British Medical Association. The European Food Safety Authority (EFSA) has also found several biotech varieties to be safe for human and animal consumption." Related links for detailed analysis of the safety of GM crops in the food chain are as follows:

Position of the American Dietetic Association:
Agricultural and Food Biotechnology
http://download.journals.elsevierhealth.com/pdfs/journals/0002-8223/PIIS0002822305021097.pdf

World Health Organization: Modern food biotechnology, human health and development: an evidence-based study
http://www.who.int/foodsafety/publications/biotech/biotech_en.pdf

United Nations:Effects on human health and the environment
http://www.fao.org/newsroom/en/news/2004/41714/index.html

National Academy of Sciences: Safety of
Genetically Engineered Foods
http://books.nap.edu/catalog/10977.html?onpi_newsdoc07272004

Food producing animals have been consuming 70 to 90 percent of genetically modified crops and co-products for more than 15 years (Flachowsky et al., 2012). A recent comprehensive review (van Eenennaam and Young, 2014) analyzed data representing over 100 billion animals fed genetically modified crops and co-products and found no evidence of adverse effects on animal health and productivity. Unfortunately, despite the absence of adverse effects, trade barriers and import restrictions have been created in some countries to prevent importation and use of corn and DDGS produced in the USA in animal feed in those countries.

Potential Physical Risk Factors

The risk of physical contaminants is extremely low. The most common physical contaminants in grain and feed ingredients are stones and fragments of metal, glass, wood or plastic. Physical hazards are classified as "hard or sharp" or "choking" hazards in food products. Agricultural production and loading facilities frequently have compacted gravel or stones which can inadvertently contaminate feed ingredients during loading. Metal to metal contact of conveyors and loading equipment can produce metal fragments during normal wear, and these fragments can occasionally be found in the grain or feed ingredient mass in transport containers or vessels. In facilities that use glass and plastic containers for storing materials, broken fragments of the materials can also contaminate feed ingredients. All of these potential physical hazards are uncommon, but can be present as a result of facilities and processes used to produce, load and transport feed ingredients.

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CHAPTER 12

Benefits and Concerns of Sulfur in DDGS

Introduction

SULFUR (S) IS AN ESSENTIAL MINERAL FOR ANIMALS and serves many important biological functions in the animal's body. The average sulfur content in DDGS is about 0.65 to 0.70 percent, but can exceed 1 percent in some samples (Table1), which limits DDGS use in ruminant diets. Sulfuric acid is commonly added during the dry grind ethanol production process to keep pH at desired levels for optimal yeast propagation and fermentation for efficient conversion of starch to ethanol. Sulfuric acid is also used for cleaning because of its lower cost relative to other acids. According to AAFCO Official Publication 2004, page 386, sulfuric acid is generally recognized as safe according to U.S. Code of Federal Regulation (21 CFR 582) and is listed as an approved food additive (21 CFR 573). In addition, corn naturally contains about 0.12 percent sulfur, and is concentrated by a factor of three, like all other nutrients when corn is used to produce ethanol and DDGS. Yeast also contains about 3.9 g/kg sulfur and they naturally create sulfites during fermentation. Based on the significant variability in sulfur content within and among DDGS sources, it is important to determine the sulfur content of the source being fed and monitor variation among lots or batches. Knowing the variation in sulfur content allows nutritionists and feed formulators the ability to provide an adequate safety margin during feed formulation to manage this variability.

However, when excess sulfur is present in ruminant diets, neurological problems can occur. When feed and water containing high levels of sulfur (greater than 0.40 percent of diet dry matter) are fed to ruminants, a condition called polioencephalomalacia (PEM) can occur. PCM is caused by necrosis of the cerebrocortical region of the brain of cattle, sheep, and goats. When sulfur is consumed by ruminants, it is reduced to hydrogen sulfide by ruminal bacteria. Hydrogen sulfide is toxic and accumulation in the rumen is thought to be the cause of these toxic effects. Ruminants are more vulnerable to PEM when their diets are abruptly changed from a primarily forage diet to a primarily grain diet. This causes a dramatic shift in rumen microbial populations that produce thiaminase, resulting in a thiamin deficiency. Sulfur also appears to have a significant role and interaction with thiaminase production to cause this condition, but the mechanism is not well understood. In addition, excess dietary sulfur can interfere with copper absorption and metabolism. As a result, when high dietary levels of sulfur are fed for an extended period of time, dietary copper levels should also be increased (Boyles, 2007). This condition does not occur in non-ruminant animals (pigs, poultry, fish).

In contrast to ruminants, feeding diets containing high-sulfur DDGS may be beneficial in avoiding metabolic stress in swine. Recent research conducted at the University of Minnesota (Song et al., 2013) showed that high sulfur content in corn DDGS protects against peroxidized lipids in DDGS by increasing sulfur-containing antioxidants in nursery pigs.

Managing Sulfur Content in Ruminant Diets When Feeding DDGS

The Beef Cattle NRC (1996) indicates the maximum tolerable level for sulfur in feedlot diets is 0.40 percent (dry matter basis). Vanness et al. (2009) summarized the incidence of PEM from University of Nebraska corn co-product feeding experiments and showed that the PEM incidence rate increases as total dietary sulfur content increases from 0.40 percent to more than 0.56 percent in diets containing six to eight percent forage (Table 2). High-sulfur diets (greater than 0.50 percent) that are low in effective fiber (less than 4 percent) and high in readily fermentable starch (greater than 30 percent) are most likely to cause PEM (Drewnoski et al., 2011). For example, Vanness et al. (2009) reported that cattle consuming a DDGS diet containing 0.47 percent sulfur with no forage had a PEM incidence rate of 48 percent, but cattle consuming a diet containing a similar concentration of sulfur with six to eight percent forage had a PEM incidence rate of less than 1 percent. Research conducted at the University of Nebraska and Iowa State University has shown that the risk for sulfur toxicity may be less when the

Table 1. Summary of studies that determined sulfur content (percent dry matter) in DDGS (adapted from Kim et al., 2012)

Reference	No. samples	Mean	SD	Minimum	Maximum
Kim et al., 2012	35	0.65	0.19	0.33	1.04
Kerr et al., 2008	19	0.69	0.23	0.38	1.35
Shurson, 2009	49	0.69	0.26	0.31	1.93

forage levels in the diets are greater than six to eight percent (Drewnoski et al. 2011). If 15 percent forage (dry matter basis) is included in the diet, total dietary sulfur concentrations can be increased to 0.5 percent, which is equivalent to an increase of 10 to 15 percent DDGS in the diet, without causing PEM. By increasing the forage content of the diet, rumen pH will not be reduced, and therefore, not favor the formation of hydrogen sulfide and allow the concentration of hydrogen sulfide to increase in the rumen. It appears feeding management strategies that minimize the risk of acidosis, such as minimizing feed intake variation, increased feeding frequency and the use of ionophores may also reduce the risk of PEM.

Table 3 shows examples of the impact of adding different dietary levels of DDGS, containing different levels of sulfur, to beef cattle diets comprised of corn and corn silage on final dietary sulfur content, assuming low sulfate levels in drinking water. These data show that at high dietary inclusion rates (40 percent of dry matter intake) and high-sulfur levels in DDGS (greater than 0.80 percent), total dietary sulfur levels would exceed the 0.40 percent considered to be the maximum level for causing PEM. The potential range of dietary sulfur content, at various DDGS dietary inclusion rates and sulfur content, assuming within plant variation of 10 percent is shown in Table 4. Therefore, when DDGS is fed to cattle, the sulfur content should be determined, and used along with the dietary inclusion rate, as well as sulfur contributions from other dietary ingredients and water, to ensure total dietary sulfur content does not exceed 0.40 percent.

In addition to the sulfur content of the feedstuffs, drinking water may also be a significant source of total dietary sulfur intake in certain geographic regions. If the sulfur content of drinking water provided to cattle is unknown, it should be tested for sulfate content and considered when determining dietary maximum diet inclusion rates of DDGS and other ingredients. Cattle water consumption also varies by geographic region and is largely influenced by ambient temperature. The additional dietary sulfur intake obtained from drinking water at various ambient temperatures and water sulfate concentrations are shown in Table 5.

Table 2. Incidence of PEM from University of Nebraska corn co-product feeding experiments (adapted from Vanness et al., 2009)

PEM incidence rate	Dietary S	PEM cases/total head
0.14 percent	0.40 to 0.46 percent	3 of 2147
0.35 percent	to 0.56 percent	3 of 566
0.56 percent	greater than 0.56 percent	6 of 99

Table 3. Effect of sulfur content of DDGS and dietary inclusion rate (dry matter basis) on total dietary sulfur content in corn-corn silage based diets for beef cattle (adapted from Boyles, 2007)

DDGS inclusion rate % dry matter	0.60 percent S in DDGS	0.80 percent S in DDGS	1.0 percent S in DDGS
20	0.21	0.25	0.29
30	0.27	0.33	0.37
40	0.33	0.41	0.49

Table 4. Range of dietary sulfur[1] based on typical within plant variation of sulfur content in DDGS (dry matter basis; adapted from Drewnoski et al., 2011)

S content expected in DDGS %	Diet S with 30 % DDGS %	Diet S with 40 % DDGS %	Diet S with 50 % DDGS %	Diet S with 60 p% DDGS %
0.6	0.32-0.34	0.36-0.38	0.40-0.43	0.44-0.48
0.7	0.35-0.37	0.40-0.43	0.45-0.49	0.50-0.54
0.8	0.38-0.40	0.44-0.47	0.50-0.54	0.56-0.61
0.9	0.41-0.44	0.48-0.52	0.55-0.60	0.62-0.67
1.0	0.44-0.47	0.52-0.56	0.60-0.65	0.69-0.74

[1] Assumes no sulfur obtained from drinking water and a maximum of 10 percent variation of DDGS sulfur content.

Table 5. Additional dietary S intake (percent) from drinking water at various ambient temperatures and water sulfate concentrations[1] (adapted from Drewnoski et al., 2011)

Water sulfate. ppm	5° C	21° C	32° C
200	0.02	0.03	0.05
400	0.04	0.05	0.10
600	0.06	0.08	0.14
800	0.09	0.11	0.19
1000	0.11	0.13	0.24

[1] Percentage of S to add to the ration to determine total dietary S intake.

Feedlot cattle appear to be most susceptible to sulfur toxicity during the first 30 days on a finishing diet when consuming high-sulfate water or high concentrations of sulfur in feed. This increased susceptibility to sulfur toxicity from feeding a high concentrate, high sulfur diet appears to be caused by a dramatic increase in rumen hydrogen sulfide concentrations which results from an increase in sulfate-reducing bacteria and a decrease in rumen pH. Because sulfate-reducing bacteria in the rumen use lactate to convert sulfur to sulfide, the increased availability of lactate during this early finishing period may increase microbial metabolism and produce more hydrogen sulfide. However, hydrogen sulfide concentrations decrease later in the finishing period due to the establishment of bacteria that use lactate, and these microbes compete with sulfate-reducing bacteria. Therefore, delaying the feeding of diets with high inclusion rates of DDGS until after the rumen microbes have adapted to a high-concentrate diet (approximately 30 days) may reduce the risk of PEM.

Feeding DDGS with High Sulfur Content to Swine

While the maximum tolerable concentration of dietary sulfur in cattle diets is fairly well established, is has not been determined for monogastric species. Sulfur is an essential component in many physiological functions of animals and is incorporated into amino acids, proteins, enzymes and micronutrients (Atmaca, 2004), but very little was known about the impact of feeding high-sulfur diets, and diets containing DDGS with a high concentration of sulfur on pig health and growth performance until recently. Kerr et al. (2011) conducted a study to evaluate the effects of dietary inorganic sulfur content on growth performance, intestinal inflammation, fecal composition and the presence of sulfate-reducing bacteria. Results from this study showed pigs can tolerate relatively high concentrations of dietary sulfur without negatively affecting growth performance, but feeding high-sulfur diets alters intestinal inflammatory mediators and intestinal bacteria.

Kim et al. (2012) conducted four experiments to determine if high concentrations of sulfur in DDGS-containing diets had negative effects on feed preference and growth performance of weanling and growing-finishing pigs. Based on the results from these four experiments, the authors concluded dietary sulfur concentration does not have adverse effects on feed preference, feed intake or growth performance of weanling or growing-finishing pigs fed corn, soybean meal and DDGS diets. In a subsequent study, Kim et al. (2012) showed that feeding 20 percent DDGS diets containing up to 0.38 percent sulfur had no detrimental effects on feed preference, feed intake or growth performance of nursery or growing-finishing pigs. An additional study conducted by Kim et al. (2014) showed that feeding 30 percent DDGS with high-sulfur content had no negative effects on growth performance of growing finishing pigs, and did not affect carcass characteristics or tissue sulfur concentrations.

In fact, elevated sulfur content in DDGS appears to have beneficial effects to counteract any potential negative effects of feeding highly peroxidized DDGS sources. Peroxidative damage of lipids in feed has been shown to negatively affect pig health and growth performance (Miller and Brzezlnska-Slebodzinska, 1993; Pfalzgraf et al., 1995; Hung et al., 2017). Lipid peroxidation occurs during the production of corn DDGS. Song and Shurson (2013) analyzed corn oil extracted from 31 corn DDGS sources and showed peroxidation of oil in DDGS can be 20 to 25 times greater than found in oil from corn grain. Corn oil contains high concentrations of polyunsaturated fatty acids (PUFA), particularly linoleic acid, which is highly susceptible to lipid peroxidation (Shurson et al., 2015). Therefore, it is possible that feeding DDGS containing oxidized lipids to pigs may require supplementation of higher levels of antioxidants (e.g. vitamin E) than they are currently being fed. For example, supplementation of additional antioxidants improved growth performance in pigs fed diets containing DDGS or oxidized corn oil (Harrell et al., 2010). However, results from other studies have shown that supplementation of antioxidants had no effect on growth performance in animals under a dietary oxidative stress challenge (Wang et al., 1997b; Anjum et al., 2002; Fernández-Dueñas, 2009).

To determine if feeding the most peroxidized DDGS source identified in a previous study (Song and Shurson, 2013), had detrimental effects on growth performance of nursery pigs, Song et al. (2013) fed corn-soybean meal or 30 percent peroxidized DDGS (PV = 84.1 mEq.kg oil; TBARS = 5.2 ng MDA/kg oil; 0.95 percent sulfur) diets containing one of three levels of vitamin E (none, 11 IU/kg, or 110 IU/kg). Serum α-tocopherol concentrations were greater in pigs fed DDGS diets containing no supplemental vitamin E, or 11 IU/kg of supplemental vitamin E compared to those fed the control diet. Furthermore, pigs fed the DDGS diets had greater serum concentrations of sulfur-containing amino acids (Met and taurine), compared with pigs fed the control diet. Liver glutathione concentration was also greater in pigs fed the DDGS diets compared with those fed the control diet, and enzyme activity of glutathione peroxidase was also increased. These results suggest the increased concentrations of sulfur-containing antioxidants (Met, taurine, glutathione) may protect pigs against oxidative stress when feeding highly peroxidized DDGS sources to pigs, and feeding elevated concentrations of vitamin E in diets may not be necessary to protect pigs against oxidative stress when feeding a high-sulfur and highly peroxidized DDGS source.

To further evaluate the effects of feeding a highly peroxidized DDGS to sows and their offspring through the nursery period, Hanson et al. (2015) fed corn-soybean meal control diet during gestation and lactation, or 40 percent DDGS gestation diets and 20 percent DDGS lactation diets to sows. At weaning, pigs from these litters were fed 0 percent, or 30 percent peroxidized DDGS (PV = 84.1 mEq.kg oil; TBARS = 5.2 ng MDA/kg oil; 0.95 percent sulfur) with supplemental vitamin E at five times the NRC (2012) requirement. Pigs from sows fed DDGS had lower serum vitamin E concentrations during preweaning and post weaning compared to pigs from sows fed the control diet. During the nursery period, pigs fed the DDGS diets had greater ADFI than pigs fed the control diet, but ADG was not different among treatments. Furthermore, feeding the 30 percent peroxidized DDGS diets during the nursery period increased serum vitamin E, but had no effect on serum TBARS or glutathione peroxidase. Perhaps the most interesting finding of this study was the serum concentrations of sulfur amino acids was about 40 to 50 percent greater compared with pigs fed the control diets, which was likely due to the greater sulfur amino acid intake of pigs fed the DDGS diets. Therefore, the antioxidant properties of sulfur amino acids appeared to be sufficient to overcome the potential negative effects on growth performance and oxidative status from feeding peroxidized DDGS, and likely spared vitamin E so the additional supplementation of vitamin E was not needed.

In summary, feeding diets containing up to 0.38 percent sulfur from DDGS and inorganic sources has no detrimental effects on growth performance, carcass characteristics and tissue sulfur concentration of pigs. Furthermore, there is some evidence DDGS containing high concentrations of sulfur (0.95 percent), when added at 30 percent to diets for weaned pigs, results in increased antioxidant protection provided by sulfur-containing amino acids.

Conclusions

Feeding strategies that increase forage intake, reduce variability in feed intake and stabilize rumen pH will reduce the risk of sulfur toxicity when feeding high-sulfur diets to ruminants. Providing 15 percent roughage in the finishing diet after 30 days on a high-concentrate diet will allow feeding diets containing up to 0.50 percent sulfur without the risk of sulfur toxicity. Determining the variability in DDGS sulfur content from various lots or batches received at a feed mill or feedlot will allow for determining acceptable safety margins for use in formulating ruminant diets. Water sulfate content and consumption must also be considered when managing total sulfur intake of feedlot cattle. In contrast, feeding 30 percent DDGS diets containing highly oxidized lipid and high sulfur (0.95 percent) has been shown to increase sulfur-containing antioxidants and prevent metabolic oxidative stress in young pigs. Feeding diets containing up to 0.38 percent sulfur from DDGS and inorganic sources has no detrimental effects on growth performance, carcass characteristics and tissue sulfur concentration of pigs

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CHAPTER 13

Reduced-Oil DDGS in Aquaculture Diets

Introduction

AQUACULTURE IS ONE OF THE FASTEST GROWING SEGMENTS of the food animal industries in the world. In 2014, the global per capita fish supply was a record high of 20 kg, which was primarily attributed to the rapid growth in aquaculture (FAO, 2016). In fact, the global aquaculture provides about 50 percent of the total fish used for human consumption (FAO, 2016). Total inland and marine aquaculture production reached 73.8 million tons in 2014 which represents a "first-sale" value of over US$160 billion (FAO, 2016). Of this total, 49.8 million tons were derived from finfish, 16.1 million tons were from molluscs, 6.9 million tons were from crustaceans, and 7.3 million tons were comprised of other aquatic animal including amphibians (FAO, 2016). The major aquaculture-producing countries are China (45.5 million tons), followed by India, Vietnam, Bangladesh and Egypt (FAO, 2016).

Historically, fish meal has been used as major component in most aquaculture diets because of its high protein content, well-balanced profile of highly digestible amino acids, significant amounts of essential fatty acids, high digestible energy content as well as its vitamin and mineral content (Abdelghany, 2003). However, the decreased availability of fish meal and increasing cost, along with sustainability concerns, have caused nutritionists and feed manufacturers to seek less expensive, high-quality alternative plant-based ingredients to partially or completely replace fish meal in aquaculture feeds. Unfortunately, replacement of fish meal with plant-based feed ingredients can result in reduced growth performance (Mbahinzirek et al., 2001; Sklan et al., 2004; Gatlin et al., 2007), unless an adequate amount of other ingredients or dietary supplements are added to these diets to meet nutrient requirements, especially amino acids. However, when two or more complimentary plant protein sources (DDGS and soybean meal) are added, it is feasible to replace all of the fish meal in the diet. Furthermore, unlike other animal species, energy and digestible nutrient requirements are poorly defined for most aquaculture species, and energy and nutrient digestibility have not been determined for most feed ingredients used in aquaculture diets. Therefore, both of these challenges make it difficult to develop precision nutrition feeding programs for various aquaculture species to the extent currently being used for other food animal species. One of the greatest challenges limiting the successful use of alternative plant-based ingredients, including corn DDGS, in aquaculture feeds is having knowledge of energy and amino acid composition and digestibility. Although there has been much less research conducted to evaluate the feeding applications of corn DDGS to various aquaculture species compared with dairy, beef, swine and poultry, this chapter summarizes all of the available information related to optimizing DDGS use in aquaculture diets.

Nutritional Value of DDGS in Aquaculture Feeds

Corn DDGS is a high energy, mid-protein, high digestible phosphorus ingredient. However, nutrient content and digestibility can vary significantly among sources (see Chapter 4 for detailed nutrient content and variability). The energy in corn DDGS is derived from its relatively high oil content (5 to 12 percent crude fat), with lesser amounts contributed from residual starch, fiber and protein. Although no studies have been conducted to compare energy digestibility of traditional high oil DDGS and reduced-oil DDGS for aquaculture species, it is assumed based on several studies with swine and poultry that crude fat content is a poor single predictor of digestible energy content among DDGS sources with variable oil content for aquaculture species. While the crude fat content of DDGS varies, corn oil in DDGS contains about 58 percent linoleic acid, 8 percent linolenic acid and 0.14 percent DHA. As a result, DDGS has a high omega 6 to omega 3 ratio. The starch content in DDGS is low, and can range from 1.1 to 7.9 percent (dry matter basis) depending on the extent starch is fermented by yeast to produce ethanol during the DDGS production process (Anderson et al., 2012). It is not known if the starch present in DDGS is digestible or in the form of resistant starch. The average crude fiber, acid detergent fiber, neutral detergent fiber and total dietary fiber (TDF) content in DDGS is 6.6, 11.1, 37.6, and 31.8 percent, respectively, and the majority (96.5 percent) of TDF is insoluble fiber (Urriola et al., 2010). Neutral detergent fiber content is one of the most variable nutritional components in DDGS, and it is unclear whether this is due to the high variability in analytical measurement among laboratories, or if corn fiber content is this variable among DDGS sources. Fiber digestibility of DDGS has not been determined in fish, but studies conducted with other monogastric species indicate a portion of this fiber can be digested and fermented to produce volatile fatty acids in the lower gastrointestinal tract, but the extent of this is variable within and among monogastric species. It appears fish with greater ability to use high-fiber diets (e.g. tilapia, catfish) perform well at high dietary DDGS inclusion rates compared with species (e.g. salmon and trout) with very little lower gut fermentation.

Despite the relatively high crude protein content in DDGS (27 percent), lysine, methionine, threonine and tryptophan concentrations are relatively low relative to the amino acid requirements of fish. Furthermore, lysine content is the most variable of all amino acids among DDGS sources, and its digestibility is also variable due to the extent of heating during the DDGS production processes used by various ethanol plants. As a result, fish diets requiring high protein levels must be supplemented with crystalline amino acids when significant amounts of DDGS are added. Apparent digestibility of amino acids in DDGS have been determined in rainbow trout diets, and are relatively high (greater than 90 percent for all essential amino acids except threonine; Cheng and Hardy, 2004a) Recents studies by Magalhães et al. (2015) have also determined apparent amino acid digestibility of corn DDGS for European seabass and meagre, and Lech and Reigh, (2012) determined apparent amino acid digestibility of corn DDGS for pompano, but amino acid digestibility has not been determined for other fish species.

The phosphorus content in DDGS (0.85 percent) is greater than in other plant-based ingredients, and much of the phytate phosphorus is released during corn fermentation in ethanol production, making it highly digestible for monogastric species. However, DDGS phosphorus digestibility and availability values have not been determined in fish. Other macrominerals such as calcium, chlorine and potassium are found in low concentrations in DDGS relative to fish requirements and must be supplemented (Hertrampf and Piedad-Pascual, 2000). Furthermore, trace minerals such as zinc, iron, manganese and copper concentrations in DDGS are lower than typically found in fish meal, but requirements can easily be met with diet supplementation of these micronutrients in premixes.

Vitamins, including riboflavin, niacin, pantothenic acid, folic acid and choline are about three times higher in DDGS than found in corn (Hertrampf and Piedad-Pascual, 2000). Limited data are available regarding the xanthophyll content and bioavailability in DDGS, or its impact on flesh color in fish. Based on limited data, the xanthophylls content in corn DDGS is highly variable and ranges from 20 to 50 mg/kg. Therefore, depending on the amount of corn and corn co-products in the diets for some fish species (e.g. catfish), diet formulation constraints on total xanthophyll content to avoid yellow pigmentation of fish fillets.

One of the distinct advantages of DDGS compared with other plant-based ingredients, is that it does not contain anti-nutritional factors found in soybean meal (trypsin inhibitors; Wilson and Poe, 1985; Shiau et al., 1987), rapeseed meal (glucosinolates and erucic acid) and cottonseed meal (gossypol; Jauncey and Ross, 1982; Robinson, 1991), and contains low levels of phytate compared with other plant-derived feed ingredients. Therefore, the lack of anti-nutritional factors and the relatively high energy, digestible amino acid and phosphorus content make it a nutritionally and economically attractive feed ingredient for use in various aquaculture species.

Abalone (Haliotis discus hannai)

Abalone (Haliotis discus hannai) is one of the most commercially important shellfish species in East Asia, especially in China, Korea and Japan. Commercial culture techniques have been successfully developed and implemented for abalone and production has been rapidly increasing in an attempt to meet demand for human consumption (Cho, 2010). Unfortunately, no studies have been published to evaluate the use of corn DDGS in abalone diets. However, Choi et al. (2014) conducted a study to evaluate the addition of increasing dietary levels (0, 15, 30, 45 and 60 percent) of rice distillers dried grains (RDDG) to replace wheat flour and soybean meal in juvenile abalone diets on growth performance and body composition. Weight gains of juvenile abalone fed the 15 and 30 percent RDDG were not different than those fed the control diet, but feeding 45 or 60 percent RDDG diets resulted in reduced weight gains compared to those fed the 0 percent RDDG diet. Survival, shell length and shell width, and soft body proximate chemical composition were not affected by dietary RDDG inclusion rate. These results suggest that adding up to 30 percent RDDG to juvenile abalone diets can provide acceptable growth performance and soft body composition. Research is needed to determine if corn DDGS can provide similar results.

Black Seabream (Acanthopagrus schlegeli)

Black seabream (Acanthopagrus schlegeli) is a commercially important marine fish species in Asia because it is known for its fast growth rate, and its seedling production and culture techniques are well established. Although there is no information on the use of corn DDGS in black seabream diets, a recent study conducted by Rahman et al. (2013) evaluated feeding increasing dietary levels of rice DDGS to juvenile black seabream. Results from this study showed that rice DDGS was a suitable replacement for wheat flour and gluten meal, and can be added up to 24 percent of the diet to achieve optimal growth performance of juvenile black seabream. Studies are needed to determine if similar responses can be achieved at these dietary inclusion rates for corn DDGS.

Channel Catfish (Lctalurus punctatus)

A summary of optimal dietary DDGS inclusion rates and experimental conditions of 13 published studies for channel catfish, catfish hybrids and swai is shown in Table 1. Initial studies on feeding corn DDGS to channel catfish were conducted in the early 1990s using traditional high-oil (greater than 10 percent crude fat) DDGS. Tidwell et al. (1990) conducted an experiment over an 11-week period where channel catfish fingerlings were fed diets containing 0, 10, 20 and 40 percent DDGS by replacing some of the corn and soybean meal. After the 11-week feeding period, there were no differences in individual fish weight, percentage survival, feed conversion or protein efficiency ratio among dietary treatments. Similarly, Webster et al. (1993) fed diets containing 0, 10, 20 or 30 percent DDGS to cage reared juvenile catfish, in which DDGS partially replaced corn and soybean meal in the diets. There were no differences in individual fish weights, survival, feed conversion carcass composition, carcass waste (head, skin, viscera) and organoleptic properties of the fillets among dietary treatments. Results from this study indicate up to 30 percent DDGS can be added to channel catfish diets with no negative effects on growth performance, carcass composition or flavor qualities of the fillets. Therefore, DDGS has been considered to be an acceptable ingredient in diets for channel catfish for nearly 30 years (Tidwell et al., 1990; Webster et al., 1991; Webster et al. 1993).

Additional studies were subsequently conducted by Robinson and Li (2008), Lim et al., (2009), and Zhou et al. (2010) to further evaluate the use of high-oil DDGS sources in catfish diets. Robinson and Li (2008) conducted two experiments to evaluate the use of cottonseed meal, DDGS and synthetic lysine as replacements for soybean meal in channel catfish diets. Fish fed the DDGS and soybean meal diet had improved (experiment 1), or similar (experiment 2) weight gain and feed conversion in both experiments compared with fish fed the control diets. Body fat tended to increase for fish fed the DDGS diets compared to those fed the control diet. Results from this study confirmed that adding up to 30 percent DDGS to channel catfish diets supports satisfactory growth performance when the diet is supplemented with synthetic lysine. Lim et al. (2009) fed diets containing 0, 10, 20, 30 and 40 percent DDGS with supplemental synthetic lysine to partially replace soybean meal and corn meal (on an equal protein basis) to juvenile catfish (13 g body weight) for 12 weeks. Results from this study showed growth performance and feed conversion were similar among dietary treatments, but body fat increased and body moisture decreased when fish were fed diets containing DDGS compared to those fed the control diet. Similarly, Zhou et al. (2010) replaced soybean meal and corn meal in juvenile hybrid catfish (channel catfish × blue catfish I. Furcatus) and observed that diets containing 30 percent DDGS provided good growth, feed conversion and protein retention. Overall, the results of these studies indicate that relatively high (30 to 40 percent) dietary inclusion rates of DDGS can be used without negatively affecting survival, growth or feed conversion of catfish. Most studies showed that whole body fat increases when feeding DDGS diets at high dietary inclusion rates, but does not appear to affect fillet color.

Unfortunately, the majority of published studies evaluating the addition of corn DDGS to aquaculture feeds did not provided detailed information about the nutrient composition of the DDGS sources fed. Therefore, it is assumed the majority of these studies used traditional, high oil (greater than 10 percent crude fat) DDGS sources. However, a recent study conducted by Renukdas et al. (2014) evaluated feeding 20 percent reduced-oil DDGS to channel and hybrid catfish and showed it can be successfully used without negative effects on growth performance or processing characteristics.

Table 1. Summary of published studies evaluating the effects of feeding corn DDGS to channel catfish (Ictalurus punctatus), catfish hybrids (I. punctatus × I. furcatus) and swai (Pangasius hypophthalmus) on growth performance and flesh composition

Fish body weight (initial – final, g)	DDGS %	Ingredients replaced	Trial duration, days	Fishmeal percent	Supplemental lysine %	Optimum DDGS %	Flesh composition	Reference
Channel catfish (Ictalurus punctatus)								
21 - 265	0 - 20	corn,soybean meal	186	0	0.15 - 0.25	20	Shank fillet yield was reduced	Renukdaset al., 20141
Varied among experiments	0 - 40	soybeanmeal	330(Exp.1) 120(Exp.2) 165(Exp.3)	0 - 1	0 - 0.80	30 to 40	Fillet fat increased	Robinson and Li, 2012

Table 1. Summary of published studies evaluating the effects of feeding corn DDGS to channel catfish (Ictalurus punctatus), catfish hybrids (I. punctatus × I. furcatus) and swai (Pangasius hypophthalmus) on growth performance and flesh composition

Fish body weight (initial – final, g)	DDGS %	Ingredients replaced	Trial duration, days	Fishmeal percent	Supplemental lysine %	Optimum DDGS %	Flesh composition	Reference
9.1 - 80.4	0 - 30	corn,soybean meal, wheat midds	56	5	0.30	30	Fillet protein wasdecreased	Li et al., 2011
12.6 - 156.7	0 - 30	corn,soybean meal	63	0	0.30 - 0.39	30	Fillet fat increased and protein decreased	Li et al., 2010
86 - 491	0 - 30	corn,soybean meal, wheat midds	150	0	0.10 - 0.20	Up to 30	No effect	Zhou et al., 2010a
13.3 - 67.1	0 - 40	corn,soybean meal	84	8	0.40	40	Wholebodyfat increased	Lim et al., 2009
48 - 1,227	0 - 40	soybean meal, wheat midds	330	1	0.80 - 0.28	30 to 40	Fillet fat increased	Robinson and Li, 2008
33 - 226	0 - 30	corn,soybean meal	110	8	none	30	No effect	Webster et al., 1993
12.4 - 54.5	0 - 35	fish meal, corn	84	0	0 - 0.4	35	-	Webster et al., 1992
10 - 79.3	0 - 70	corn,soybean meal	84	10	0 - 0.4	35/70	Whole body protein decreasedand fat increased	Webster et al., 1991
1.5 – 17.3	0 - 40	corn,soybean meal	77	8	none	40	-	Tidwell et al., 1990
Hybrid catfish (I. punctatus × I.furcatus)								
47 - 703	0 - 20	corn,soybean meal	186	0	0.15 - 0.25	20	No effect	Renukdaset al., 2014[1]
1.2 - 8.7	0 - 30	corn,soybean meal, wheat midds	56	0	0.2	30	-	Zhou et al., 2010b
Swai (Pangasius hypophthalmus)								
40 - 500	0 - 15	soybean meal, rice bran	118	4.5 - 5.8	0	15	No effect	U.S. Grains Council, 2015

[1] Diets contained reduced-oil DDGS

Common carp (Cyprinus carpio)

Common carp is the third most widely cultivated and commercially important freshwater fish species in the world, especially in Asia and some European countries (Rahman, 2015). It is an attractive species for commercial aquaculture production because it is highly adaptable to various foods and environments (Rahman, 2015). Unfortunately, limited information is available about optimum dietary inclusion rates of DDGS in carp diets. One feeding trial, sponsored by the U.S. Grains Council, was conducted at the Hoa Binh reservoir in Hoa Binh Province in Vietnam, to determine the optimum inclusion rate of DDGS in diets for common carp (U.S. Grains Council, 2007a). Common carp with initial body weight of 26 to 51g were placed in floating cages and fed diets containing 0, 5, 10 and 15 percent DDGS for more than three months until they reached about 200 g average body weight. The four diets containing DDGS were formulated to contain similar dietary energy (2.9 Mcal/kg) and protein (26 percent) content, and were comprised of soybean meal, wheat by products, rice bran, fish meal meat and bone meal and fish oil. Results showed that increasing dietary inclusion rates of DDGS had no effect on growth rate and feed consumption, but there was a trend for fish fed the 10 percent and 15 percent DDGS diets to grow at a faster rate (40 g/month) than the fish fed diets containing 0 percent and 5 percent DDGS (28 g/month). Fish survival rates were very high (99.3-99.5 percent) and there were no differences among dietary treatments. Fish flesh composition was determined at the end of trial and there were no differences in moisture, protein and fat content and flesh color among dietary treatments. In conclusion, it appears corn DDGS can be included in common carp diets up to 15 percent without negatively affect growth performance and meat quality of common carp.

European Seabass (Dicentrarchus labrax)

European seabass (Dicentrarchus labrax) is a popular and well established aquaculture species in the Mediterranean. A recent study conducted by Magalhães et al. (2015) determined the apparent digestibility of two sources of corn DDGS (Spain, 11.8 percent crude fat; Hungary, 12.8 percent crude fat on dry matter basis) in juvenile European seabass and results are shown in Table 2. Although the two DDGS sources had similar nutrient composition, the apparent digestibility of dry matter, energy and crude protein was greater in the corn DDGS source from Spain compared with the corn DDGS source from Hungary. Variability in nutrient content and digestibility of DDGS sources is a challenge for nutritionists when determining economic value and digestible energy and nutrient content for formulating precision aquaculture diets. The relatively low apparent digestibility coefficients for dry matter and energy observed in this study were likely due to the relatively high fiber content in corn DDGS, because fish, especially carnivorous species, have a limited ability to digest complex carbohydrates. However, the protein digestibility in both sources of DDGS was similar or greater than that of fish meal (89 to 92 percent), which was the only source of protein in the reference diet. There were no differences in amino acid digestibility between the two corn DDGS sources, but digestibility of most amino acids was generally less than in fish meal. Corn DDGS is a good source of dietary lipids, and some sources may contain greater concentrations than the lipid content of fish meal (9.2 percent). However, the apparent digestibility of lipids in the DDGS sources was less than in fish oil (98.5 percent), which was the primary lipid source used in the reference diet. Although no growth performance trials have been conducted for European seabass, the results from this study suggest corn DDGS can be a suitable partial replacement for fish meal in diets for this species.

Table 2. Apparent digestibility coefficients (percent) of energy and nutrient of two sources of corn DDGS in European seabass (adapted from Magalhães et al., 2015)

Nutritional component	Corn DDGS (Spain)	Corn DDGS (Hungary)
Dry matter	63.3^a	56.7^b
Energy	67.9^a	63.6^b
Crude protein	96.3^a	92.1^b
Lipids	89.0	87.2
Arginine	86.4	86.5
Histidine	85.1	84.1
Isoleucine	83.7	83.0
Leucine	89.1	89.0
Lysine	94.8	99.0
Methionine	78.3	83.9
Phenylalanine	81.0	85.9
Threonine	81.5	81.1
Valine	84.3	84.2

^{a,b}Means within rows with different superscripts are different (P less than 0.05)

Freshwater Prawns (Macrobrachium rosenbergii)

A few studies have been conducted on feeding diets containing high-oil DDGS to freshwater prawns. The first study was conducted by Tidwell et al. (1993a), where they fed juvenile freshwater prawns (0.66 g) one of three isonitrogenous diets (29 percent crude protein) containing 0, 20 or 40 percent DDGS. Results from this study showed no differences among dietary treatments for average yield (833 kg/ha), survival (75 percent), individual weight (57 g) and feed conversion (3.1). Therefore, feeding practical diets containing up to 40 percent DDGS results in good growth performance and survival for prawns stocked at a density of 19,760/ha.

In a subsequent study, Tidwell et al. (1993b) evaluated the effects of partially replacing fish meal with soybean meal and DDGS in diets for pond-raised freshwater juvenile prawns (0.51 g). Three diets were formulated to contain 32 percent crude protein and contained 15, 7.5 or 0 percent fish meal. Fish meal was replaced with variable amounts of soybean meal and 40 percent DDGS. There were no differences among dietary treatments for average yield, survival, individual weight and feed conversion. Replacement of fish meal with soybean meal and DDGS increased dietary concentrations of glutamine, proline, alanine, leucine and phenylalanine, while decreasing aspartic acid, glycine, arginine and lysine content in the diets. Fatty acid profiles of the diets also changed when soybean meal and DDGS replaced fish meal. Concentrations of 16:0, 18:2n-6, and 20:1n-9 increased, and concentrations of 14:0, 16:1n-7, 18:1n9, 18:3n-3, 20:5n-3, 22:5n-3 and 22:6n-3 decreased in the DDGS diets. These results suggest fish meal can be partially or totally replaced with soybean meal and DDGS in diets for freshwater prawns raised in ponds in temperate climates. Coyle et al. (1996) reported that DDGS can serve a dual purpose as feed for juvenile prawns (greater than 2 g) and serve as a pond fertilizer.

Meagre (Argyrosomus regius)

Meagre (Argyrosomus regius) is considered to be one of the most promising species for Mediterranean aquaculture diversification. Unfortunately, no studies have been performed to evaluate feeding corn DDGS to meagre on growth performance, survival and whole body composition, but Magalhães et al. (2015) recently determined the apparent digestibility of two sources of corn DDGS (Spain, 11.8 percent crude fat; Hungary, 12.8 percent crude fat on dry matter basis) in 79 g juvenile meagre (Table 3). Results from this study showed that although the two DDGS sources had similar nutrient composition, the apparent digestibility of dry matter, energy and crude protein was greater in corn DDGS source from Spain compared with the corn DDGS source from Hungary. Variability in nutrient content and digestibility of DDGS sources is a challenge when determining the economic value, as well as digestible energy and nutrient content for use when formulating aquaculture diets. The relatively low apparent digestibility coefficients for dry matter and energy were likely due to the relatively high fiber content in corn DDGS. However, the protein digestibility in both

Table 3. Apparent digestibility coefficients (percent) of energy and nutrient of two sources of corn DDGS in meagre (adapted from Magalhães et al., 2015)

Nutritional component	Corn DDGS (Spain)	Corn DDGS (Hungary)
Dry matter	65.6^{a}	57.2^{b}
Energy	67.4^{a}	58.0^{b}
Crude protein	97.9^{a}	91.8^{b}
Lipids	87.9	82.0
Arginine	81.5	82.6
Histidine	63.3	59.1
Isoleucine	75.0	76.4
Leucine	93.0	88.9
Lysine	85.0	85.6
Methionine	66.3	67.0
Phenylalanine	76.0	83.4
Threonine	81.2	91.1
Valine	81.7	81.6

[a,b] Means within rows with different superscripts are different (P less than 0.05)

sources of DDGS was similar or greater than that of fish meal (89 to 92 percent), which was the only source of protein in the reference diet. There were no differences in amino acid digestibility between the two corn DDGS sources, but digestibility of most amino acids was generally less than in fish meal. Corn DDGS is a good source of dietary lipids, and some sources may contain greater concentrations than the lipid content of fish meal (9.2 percent). However, the apparent digestibility of lipids in the DDGS sources was less than in fish oil (98.5 percent), which was the major lipid source used in the reference diet. The results from this study suggest corn DDGS can be a suitable partial replacement for fish meal in diets for meagre.

Milkfish (Chanos chanos)

Milkfish (Chanos chanos) is a primary aquaculture species in Asia, and serves as an inexpensive source of food protein for consumers in this region. In fact, milkfish was recommended by the Food and Agriculture Organization of the United Nations as one of the species suitable for commercial aquaculture production because it belongs to the lower trophic level of the food chain and does not require a high amount of dietary protein from fish meal.

The U.S. Grains Council (2007b) sponsored a demonstration trial to determine the maximal amount of corn DDGS that could be included in the diets of milkfish. Five isonitrogenous and isoenergetic diets were formulated to contain 0, 10, 20, 30 or 40 percent DDGS and fed. No differences in growth performance were observed among dietary treatments, suggesting that up to 40 percent DDGS diets can be fed to milkfish to achieve acceptable growth performance. These results were confirmed in a recent study conducted by Mamauag et al. (2017), where these researchers evaluated feeding increasing dietary levels (0, 15, 25, 30, 35 and 45 percent) of corn DDGS in isonitrogenous (35 percent crude protein) and isolipidic (6 percent crude fat) diets on growth performance, body chemical composition and intestinal morphology of milkfish for a 90-day feeding period (Table 4). Fish meal and DDGS were used as the primary sources of protein in all diets. There were no differences of dietary DDGS inclusion rate on weight gain, survival, feed intake, feed conversion and chemical body composition measurements. Apparent digestibility of protein, lipids, carbohydrates and dry matter of the corn DDGS source fed was 91, 85, 75 and 52 percent, respectively. Furthermore, there were no effects on intestinal morphology among dietary treatments. These results indicate that corn DDGS can effectively be used at levels up to 45 percent of the diet without negatively affecting growth performance, survival, body composition and intestinal morphology in milkfish.

Pacific White Shrimp (Litopenaeus vannamei)

World shrimp production has been increasing rapidly, and Pacific white shrimp (Litopenaeus vannamei) is the primary cultured shrimp species. Historically, fish meal has been used as the primary protein source in shrimp feeds because of its balanced amino acid profile, relatively high essential fatty acid and mineral content and is typically added at levels of about 20 percent in shrimp diets. However, concerns about increasing cost and long-term sustainability of using

Table 4. Effects of feeding increasing dietary levels of corn DDGS to juvenile milk fish (Chanos chanos) on growth performance, survival, and whole body composition (adapted from Mamauag et al., 2017)

	Dietary DDGS inclusion rate %					
Measure	0%	15%	25%	30%	35%	45%
Initial body weight, g	3.08	3.01	3.08	3.10	3.11	3.08
Final body weight, g	21.0	18.5	20.1	22.1	18.1	19.2
Weight gain %	582	513	553	614	483	519
Survival %	82	81	85	82	85	83
Feed intake[1]	24.2	25.1	25.1	24.1	25.0	24.0
Feed conversion[2]	0.77	0.76	0.77	0.75	0.73	0.75
Whole body composition						
Crude protein, g/kg dry matter	732	684	696	694	690	736
Crude fat, g/kg dry matter	157	194	183	164	153	142
Ash, g/kg dry matter	93	99	92	90	103	91

[1] Feed intake = g dry feed/fish/90 days

[2] Feed conversion = live weight gain (g)/dry feed intake (g)

fish meal in diets for shrimp and other aquaculture species have led researchers to explore alternative plant-based feed ingredients (e.g DDGS) as potential partial or complete replacement of fish meal in shrimp diets. Results from four studies evaluating the effects of feeding DDGS diets to Pacific white shrimp are summarized in Table 5.

Initial studies by Roy et al. (2009) showed that Pacific white shrimp had similar weight gain when fed a 10 percent DDGS diet compared with feeding other alternative feed ingredients (poultry by-product, pea meal) to replace fish meal, but lower biomass was produced due to a trend for increased mortality. However, in a subsequent study conducted by Sookying and David (2011) showed that feeding a 10 percent DDGS diet with high amounts of soybean meal to replace fish meal resulted in no differences in final weight (16.3 g), survival (92.2 percent) and feed conversion (1.32) compared with feeding the 10 percent fish meal diet (16.9 g final weight, 86.6 percent survival, and 1.35 feed conversion). Cummins et al. (2013) fed diets containing up to 30 percent DDGS with supplemental lysine to replace fish meal, and partially replace soybean meal and wheat flour and showed a reduction in growth performance.

In contrast, Rhodes et al. (2015) conducted a growth performance trial and two digestibility trials to evaluate the effects of feeding a source of reduced-oil DDGS (4.8 percent crude fat) to Pacific white shrimp. In the growth performance trial, shrimp were fed isonitrogenous diets containing 0, 10, 20, 30 or 40 percent DDGS and 6 percent fish meal, to partially replace soybean meal. Diets containing 30 percent DDGS contained 0.06 percent supplemental lysine, and 40 percent DDGS diets contained either 0 or 0.13 percent supplemental lysine. No differences were observed in final biomass, final average weight, feed conversion and survival (95 to 100 percent) of shrimp fed the 0, 20, 30 or 40 percent DDGS diets, and shrimp fed the 10 percent DDGS diet had improved final biomass, final weight and feed conversion compared with all other dietary treatments. Growth performance was similar between shrimp fed the 40 percent DDGS diets with or without supplemental lysine, indicating that lysine was not a limiting nutrient in these diets. The dry matter, energy and protein digestibility coefficients of reduced-oil DDGS were much less than those from the reference diet in both trials, and the apparent protein digestibility of reduced-oil DDGS (36.9 to 44.7 percent) was much less than the apparent protein digestibility of 78.5 percent for DDGS reported by Lemos et al. (2009) using the same species and similar experimental protocol (Table 6). These differences may be due to DDGS source, protein content, or analytical methods. These results suggest that although the apparent digestibility of dry matter, energy and protein in reduced-oil DDGS were less than in the reference diet, shrimp achieved acceptable growth performance and survival when fed 40 percent DDGS diets.

Table 5. Summary of published studies evaluating the effects of feeding corn DDGS to Pacific white shrimp (Litopenaeus vannamei) on growth performance and flesh composition

Fish body weight (initial – final, g)	DDGS %	Ingredients replaced	Trial duration, days	Fishmeal %	Supplemental lysine %	Optimum DDGS %	Reference
0.49 - 7.2	0 - 40	soybeanmeal, corn starch	56	6	0 - 0.13	40	Rhodesetal, 2015[1]
0.99 - 6.1	0 - 30	fish meal, soybeanmeal, wheat flour	56	0	0 - 0.4	Partial replacement of soybean meal with DDGS in diets containing no fish mealreducedgrowth performance	Cummins et al., 2013
0.04 - 16.3	10	sorghum	126	0	none	10	Sookyingand Davis, 2011
0.45 - 25	0 - 10	sorghum,fish meal	63	0	none	Up to 10	Roy et al., 2009

[1] Diets contained reduced-oil DDGS (4.8 percent crude fat)

Table 6. Apparent digestibility coefficients for dry matter, energy and crude protein in a reference diet and reduced-oil DDGS in Pacific white shrimp (adapted from Rhodes and Davis, 2015)

Measure	Reference diet	Reduced-oil DDGS
Trial 1		
Dry matter	68.2	53.8
Energy	74.5	55.7
Crude protein	85.7	36.9
Trial 2		
Dry matter	73.2	42.4
Energy	78.1	20.9
Crude protein	89.1	44.7

Pompano (Trachinotus carolinus)

Although there has been significant interest in producing Pompano in commercial aquaculture systems for many years, there has been minimal research conducted to determine the nutritional needs of Pompano until recently (Lazo et al., 1998; Weirich et al., 2006; Williams, 2008;.Riche, 2009; Gonzalez-Felix et al., 2010; Gothreaux et al., 2010; Riche and Williams, 2010; Lech and Reigh, 2012). Lech and Reigh (2012) determined apparent digestibility of crude protein and energy, as well as apparent availability of amino acids in corn DDGS, and compared these values with canola meal and corn gluten meal (Table 7). Apparent energy digestibility of corn gluten meal was greater than canola meal and DDGS, and energy digestibility of DDGS was greater than canola meal. Similarly, apparent crude protein digestibility was greater in corn gluten meal than DDGS, but protein digestibility of canola meal was not different compared with corn gluten meal and DDGS. Furthermore, there were no differences in amino acid availability coefficients between canola meal, corn gluten meal and DDGS except for leucine, which was greater in corn gluten meal than in canola meal and DDGS. Lech and Reigh (2012) indicated nutrient digestibility coefficients of feedstuffs vary among studies even when culture conditions, fish size and experimental methods are similar. These researchers suggested prediction equations need to be developed to estimate digestibility of energy and nutrients in feed ingredients for various species of fish, which would help standardize nutritional values for more accurate diet formulation. These researchers also suggested more information is needed on energy and nutrient digestibility for various combinations and dietary inclusion rates of ingredients to develop more realistic nutrient digestibility coefficients for use in practical diet formulations. Published nutrient availability values of feedstuffs need to not only be species specific, but also diet specific. Therefore, the nutrient composition of reference diets used in determining nutrient digestibility and availability must be considered when determining digestibility data for practical feed formulation.

Rainbow Trout (Oncorhynchus mykiss)

Feed for carnivorous fish like rainbow trout (Oncorhynchus mykiss) requires large amounts of fish meal (30 to 50 percent of the diet). As a result, due to the high price of fish meal, nutritionists continue to evaluate alternative protein sources, such as DDGS, to use as partial replacements for fish meal. Many nutritionists observe that corn DDGS may have limited nutritional value in diets for salmonids because it contains relatively high concentrations of non-strach polysaccharides and an unfavorable digestible amino acid balance. However, several studies have shown corn DDDGS is a valuable feed ingredient in rainbow trout diets and results are summarized in Table 8.

Initial studies by Cheng et al. (2003) and Cheng and Hardy (2004a, b) showed DDGS can be added at levels of 15 to 22.5 percent with the addition of supplemental lysine and or methionine to achieve acceptable growth performance, with minimal or no effect on body composition. Cheng and Hardy (2004a) reported they had unpublished data indicating apparent digestibility coefficients of protein and amino acids in DDGS were high (crude protein = 90.4 percent, essential amino acids except threonine = greater than 90 percent, and non-essential amino acids except cysteine = greater than 86 percent) for rainbow trout. However, they pointed out one of the limitations of using DDGS in rainbow trout diets is the relatively low concentrations of lysine and methionine compared with concentrations of these amino acids in fish meal. Therefore, supplemental synthetic lysine and methionine must be added to DDGS diets for rainbow trout to achieve satisfactory growth performance. To demonstrate this, Cheng and Hardy (2004a) conducted a six-week feeding trial to determine the effects of feeding diets containing 0, 7.5, 15 and 22.5 percent DDGS, with or without synthetic lysine and methionine supplementation, on growth performance of 50 g rainbow trout. Survival rate of all fish was 100 percent, and fish fed diets containing 15 percent DDGS, or replacing 50 percent of fish meal with

Table 7. Apparent digestibility of energy and crude protein, and apparent availability of essential amino acids in canola meal, corn gluten meal, and DDGS for Florida pompano (Trachinotus carolinus (adapted from Lech and Reigh, 2012)

	Canola meal	Corn gluten meal	DDGS
Apparent digestibility %			
Energy	21.3[c]	57.1[a]	30.7[b]
Crude protein	38.6[ab]	57.2[a]	20.6[b]
Apparent availability %			
Arginine	53.8	68.5	35.0
Cysteine	30.3	42.5	23.0
Histidine	46.9	58.7	30.0
Isoleucine	50.4	62.5	40.9
Leucine	46.8[b]	70.8[a]	55.6[b]
Lysine	48.4	47.9	50.4
Methionine	91.9	84.9	91.5
Phenylalanine	54.2	70.9	55.5
Threonine	44.6	56.9	37.6
Valine	48.1	64.7	50.4

[a,b,c]Means with different superscripts within rows are different (P less than 0.05).

Table 8. Summary of published studies evaluating the effects of feeding corn DDGS to Rainbow trout (Oncorhynchus mykiss) on growth performance and flesh composition

Fish body weight (initial – final, g)	DDGS %	Ingredients replaced	Trial duration, days	Fishmeal %	Supplemental lysine %	Optimum DDGS %	Flesh composition	Reference
143-359	0-50	Sunflowermeal, rapeseedmeal, field peas	77	18.9	none	50	-	Overland et al., 2013
33.6-57	0-20	Fish meal, wheat	36	30-40	0.50	none	Whole body fat increased when fed 20 percent	Barnes et al., 2012
21-158.4	0-30	In combination with corn gluten meal replaced fish meal and wheat flour	84	0	none	30	Whole body protein decreased and fat increased	Stone et al., 2005
49.8-96.2	0-22.5	In combination with corn gluten meal replaced fish meal and wheat flour	42	7.5-22.5	0-1.23	15/22.5	Whole body fat decreased at 22.5 percent without supplemental lysine, but not when supplemental lysine was added	Cheng and Hardy, 2004a
20.0-78.5	15	-	70	15	0.82	15	No effect	Cheng and Hardy, 2004b
49.5 -114.6	18.5	Herring meal, wheat, corn gluten	49	17.5	0-0.48	18.5 when diets were supplemented with methionine	No effect	Cheng et al., 2003

DDGS on an isonitrogenous and isocaloric basis, resulted in similar weight gain and feed conversion compared to fish fed the fish meal-based diet. These results indicate DDGS, without synthetic lysine and methionine supplementation, can be added to the diet up to 15 percent, or replace up to 50 percent of the fish meal to achieve satisfactory growth performance. In addition, DDGS can be used up to 22.5 percent, or replace up to 75 percent of the fish meal in rainbow trout diets with appropriate synthetic lysine and methionine supplementation. Cheng et al. (2003) showed that when soybean meal, DDGS and 1.65 g/kg of methionine hydroxyl analogue (MHA) were added to rainbow trout (50 g in initial body weight) diets to replace 50 percent of the fish meal, weight gain, feed conversion, crude protein and phosphorus retention were significantly improved compared to fish fed an equivalent diet without MHA supplementation.

Cheng and Hardy (2004b) also evaluated the effects of phytase supplementation on apparent digestibility coefficients of nutrients in DDGS, as well as growth performance and apparent nutrient retention of rainbow trout-fed diets containing DDGS, phytase, and varying levels of a trace mineral premix. Apparent digestibility coefficients in DDGS diets (30 percent inclusion rate) containing different levels of phytase (0, 300, 600, 900 and 1200 FTU/kg of diet) ranged from 49 to 59 percent for dry matter, 79 to 89 percent for crude fat, 80 to 92 percent for crude protein, 51 to 67 percent for gross energy, 74 to 97 percent for amino acids, and 7 to 99 percent for minerals. When DDGS was included at a rate of 15 percent of the diet, and supplemented with lysine, methionine and phytase, but adding different levels of trace mineral premix, there were no differences in weight gain, feed conversion, survival, body composition and apparent nutrient retention among fish fed all diets, except for fish fed a diet without trace mineral supplementation. These results suggest that phytase was effective in releasing most of the minerals, and that trace mineral supplementation could be reduced when phytase is added to rainbow trout diets.

In a subsequent study, Stone et al. (2005) evaluated the effects of extrusion on nutritional value of diets containing corn gluten meal and corn DDGS for rainbow trout and observed that the extent of fish meal replacement in the diet depends upon the ratio of DDGS to corn gluten meal used. Their results suggest that up to 18 percent of the diet can be comprised of these corn co-products to replace about 25 percent of the fish meal without negatively affecting growth performance. They also found that extrusion of diets containing corn DDGS and corn gluten meal was of no benefit compared to feeding cold-pelleted diets.

The most recent study evaluating corn DDGS in rainbow trout diets was conducted by Øverland et al. (2013) to evaluate the addition of 25 or 50 percent DDGS to replace sunflower meal, rapeseed meal and field peas. Feeding the 50 percent DDGS diet resulted in greater feed intake and weight gain, and improved feed conversion compared with feeding the control diet containing fish meal and plant protein ingredients and the 50 percent DDGS diet. However, there were no differences in digestibility of protein, most amino acids and phosphorus among diets, and feeding the DDGS diets tended to increase energy digestibility. In fact, feeding the 50 percent DDGS diet resulted in greater energy and phosphorus retention than trout fed the control diet, and had greater nitrogen retention than fish fed the control or 25 percent DDGS diets. Furthermore, feeding the DDGS diets had no effect on weight of the distal intestine, intestinal enzyme activity or plasma metabolites. These results show corn DDGS is a suitable energy, protein and phosphorus source for rainbow trout when substituted for plant-based feed ingredients.

Red claw crayfish (Cherax quadricarinatus)

Interest in growing Australian red claw crayfish (Cherax quadricarinatus) in culture has been increasing in recent years, and this species is currently being commercially produced in several countries including China, Mexico and Australia. Red claw crayfish can be fed commercially prepared diets and grow rapidly over a relatively short period of time (117 days; Thompson et al. (2004). This species is popular among seafood consumers because of its excellent tail-meat flavor, lobster-like appearance, are larger than shrimp and have excellent storage quality. Thompson et al. (2006) evaluated feeding 18 or 28 percent crude protein diets (containing sorghum, soybean meal and 18.3 or 30 percent corn DDGS to replace fish meal) to 5.75 g juvenile red claw crayfish for 97 days on growth performance and body composition. Results from this study showed using corn DDGS and soybean meal to replace fish meal in 28 percent protein diets had no effect on feed conversion, survival and body composition, which suggests DDGS can be used effectively in this feeding application.

Sunshine bass (Morone chrysops x M-saxatilis)

Striped bass (Morone saxatilis) and Morone hybrids are a significant source of food fish, and rank first in volume among recreational fisheries in the U.S. However, as for most aquatic fish species, limited research has been conducted to evaluate the benefits and limitations of feeding corn DDGS to striped bass and associated hybrids.

An initial study was conducted by Webster et al. (1999), where juvenile (15 g) sunshine bass (Morone saxatilis × M. saxatilis) were fed a 40 percent protein diet containing 10 percent DDGS to replace fish meal, corn and meat and bone meal, on growth performance and body composition during an eight-week feeding period. Results from this study showed that feeding a 10 percent DDGS diet provides acceptable growth performance with no adverse effects on flesh composition. More recently, Thompson et al. (2008) evaluated digestibility of dry matter, protein, lipid and organic matter of two fish meals, two poultry by-product meals, soybean meal and DDGS in practical diets for sunshine bass. Fish fed DDGS had the lowest apparent digestibility coefficients for protein (65 percent) and organic matter (17 percent) compared to menhaden fish meal, which had the highest protein and organic matter digestibility coefficients (86 and 89 percent, respectively). The quality of the DDGS source used was not defined, but was likely of inferior quality due to the poor protein and organic matter digestibility observed in this study. These results are in contrast to results of several other studies involving various other fish species, where some level of DDGS inclusion in diets provided satisfactory performance. These results indicate only high quality DDGS sources should be used in aquaculture feeds to achieve satisfactory growth performance and nutrient digestibility.

Tilapia (Oreochromis niloticus)

Tilapia (Oreochromis niloticus) is one of the most popular and economically important warm water fish grown throughout the world. As a result, the majority of studies (n = 23) related to feeding corn DDGS to various aquaculture species, have been conducted with tilapia and results of these studies are summarized in Table 9.

The first studies evaluating the addition of corn DDGS to tilapia diets were conducted by Wu et al. (1994, 1996, 1997). Wu et al. (1994) reported that feeding diets containing either corn gluten meal (18 percent) or DDGS (29 percent) and 32 percent or 36 percent crude protein, resulted in improved weight gains for tilapia (initial weight of 30 g) than fish fed a commercial diet containing 36 percent crude protein and fish meal. In a subsequent study, Wu et al. (1996) evaluated the growth responses for smaller tilapia (0.4 g initial weight) fed diets containing up to 49 percent DDGS, up to 42 percent corn gluten feed, or up to 22 percent corn gluten meal, at dietary crude protein levels of 32 percent, 36 percent and 40 percent during an eight-week feeding period. Of the eight diets fed, the highest weight gain was achieved by feeding the 36 percent protein commercial control diet and the 40 percent protein diet containing 35 percent DDGS. The most improvement in feed conversion was achieved by feeding the control diet (1.05) and two 40 percent protein diets containing either the 35 percent DDGS diet (1.13) or 30 percent corn gluten feed diet (1.12). The highest protein efficiency ratio (weight gain/protein fed) was obtained by feeding the control diet (3.79) and two 36 percent protein diets containing 49 percent DDGS (3.71) or 42 percent corn gluten feed (3.55). From these results, these researchers concluded feeding diets containing 32 percent, 36 percent, and 40 percent protein, and 16 to 49 percent corn co-products provided acceptable weight gains, feed conversion and protein efficiency ratio for tilapia fry.

When using DDGS in aquaculture diets, the addition of supplemental synthetic amino acids is often necessary when formulating relatively low protein diets containing high amounts of corn co-products (e.g. DDGS, corn gluten feed, corn gluten meal) to avoid amino acid deficiencies, especially lysine, to support satisfactory growth performance. To do this, Wu et al. (1997) evaluated growth performance of tilapia fry (0.5 g initial weight) over an eight-week feeding period by feeding diets containing 28 or 32 percent protein, supplemental synthetic lysine and tryptophan and 54 to 92 percent corn co-products. There were no differences in feed conversion and protein efficiency ratio among fish fed the 28 percent protein diet containing 82 percent DDGS with supplemental synthetic lysine and tryptophan, compared with the 67 percent gluten feed and 26 percent soy flour diet and the control 32 percent protein diet. Based on these results, DDGS, corn gluten feed and corn gluten meal can be successfully used, along with adequate amounts of synthetic amino acids, to formulate diets containing all plant-based ingredients to replace all of the fish meal for juvenile tilapia.

A subsequent study conducted by Tidwell et al. (2000), evaluated growth performance, survival and body composition of cage-cultured Nile tilapia fed pelleted and unpelleted DDGS diets in polyculture with freshwater prawns. Growth rate was improved for fish fed the pelleted DDGS diet compared with those fed the unpelleted DDGS diet, but feeding a commercial catfish diet resulted in increased individual body weight and length, growth rate and feed conversion compared to fish fed the pelleted or unpelleted DDGS diets. Although growth was significantly increased for fish fed the commercial diet, the cost of production was significantly higher ($0.66/kg gain) compared to fish fed the unpelleted and pelleted DDGS diets ($0.26/kg gain and $0.37/kg gain, respectively). Prawn production resulted in 1,449 kg/ha, and adding tilapia in polyculture increased total pond productivity by 81 percent. These researchers concluded that feeding DDGS provided more economical growth of tilapia and that polyculture of prawns and tilapia may improve overall pond efficiency in freshwater ponds in temperate climates.

In another study, Lim et al. (2007) fed juvenile Nile tilapia (9.4 g in body weight) diets containing 0, 10, 20, 40 percent DDGS and 40 percent DDGS with supplemental synthetic lysine, as partial replacements for soybean meal and corn meal, for 10 weeks during a Streptococcus iniae challenge. Fish fed the 40 percent DDGS diet had the lowest weight gain, protein efficiency ratio, whole body protein and poorest feed conversion, but supplementing the 40 percent DDGS diet with synthetic lysine improved weight gain and protein efficiency ratio. However, feeding diets containing DDGS had no effect on number of days to first mortality, cumulative mortality at 14 days post-challenge, or on hematological and immunological parameters. These researchers concluded that up to 20 percent DDGS can be added to Nile tilapia diets as a partial substitute for soybean

Table 9. Summary of published studies evaluating the effects of feeding corn DDGS to Nile tilapia (Oreochromis niloticus), red tilapia and hybrid tilapia (O. aureus × O. niloticus) on growth performance and flesh composition

Fish body weight (initial – final, g)	DDGS %	Ingredients replaced	Trial duration, days	Fishmeal %	Supplemental lysine %	Optimum DDGS %	Flesh composition	Reference
Nile tilapia (Oreochromis niloticus)								
21 - 183	52.4	fish meal, soybean meal, poultry by-product meal, wheat flour, starch,	168	0 - 10	0.4	50	No effect on fillet color and amino acid composition, but increased n-6 fatty acids	Herath et al., 2016
6.4 - 32.0	17	soybean meal	56	0	0 - 1.0	High lysine corn protein concentrate can be used to balance the amino acid composition of the diet without adding crystalline lysine	-	Nguyen and Davis, 2016
0.98 - 14.2	0 - 40	corn, soybean meal	84	11	none	20 percent without enzymes, 30 percent with enzymes	Whole body protein increased with 10 and 20 + enzymes, 40 increased body fat	Soltan et al., 2015
6.0 - 28.3	0 - 20	corn, fish meal	72	11 - 20	none	16	No effect	Gabr et al., 2013
6.0 - 28.3	0 - 20	corn, soybean meal	72	20	none	10	greater than 5 decreased whole body protein and increased ash and crude fat	Khalil et al., 2013
27.1 – 286	0 - 15	fish meal	123	0 - 15	none	15 percent for best economic efficiency, 11.25 percent for best growth	Whole body protein and ash decreased, but lipid and energy content increased	Abdelhamed et al., 2012
18.6 - 35.7	0 - 30	corn, soybean meal	84	20	0 - 0.6	30	-	Ibrahim et al., 2012
34.9 - 67.7	0 - 27.5	corn, soybean meal	55	5	none	17.5	-	Schaeffer et al., 2010

Table 9. Summary of published studies evaluating the effects of feeding corn DDGS to Nile tilapia (Oreochromis niloticus), red tilapia and hybrid tilapia (O. aureus × O. niloticus) on growth performance and flesh composition

Fish body weight (initial – final, g)	DDGS %	Ingredients replaced	Trial duration, days	Fishmeal %	Supplemental lysine %	Optimum DDGS %	Flesh composition	Reference
6.7 – 11	0 - 40	corn, soybean meal	42	5	none	20	-	Schaeffer et al., 2009
3.8 - 35	28	-	82	10	none	Supplementation of 57 to 150 mg/kg phytase improved growth and feed conversion in DDGS diets	-	Tahoun et al., 2009
2 - 23	0 - 55	corn, soybean meal	70	10	0 - 0.4	28 to 55	-	Abo-State et al., 2009
6.7 - 68.6	0 - 60	corn, soybean meal	84	8	0.9	Up to 60	-	Shelby et al., 2008
9.4 - 60.5	0 - 40	corn, soybean meal	70	8	0 - 0.4	20 to 40	Whole body protein decreased at 40 percent	Lim et al., 2007
2.7 - 68.5	0 - 30	fish meal, soybean meal	70	0 - 8	none	30	No effect	Coyle et al., 2004
26 - 120	0 - 100	-	84	0	none	-	No effect	Tidwell et al., 2000
0.5 - 11.4	0 - 82	corn gluten feed, soybean meal	56	0	0.25 - 0.75	none	-	Wu et al., 1997
0.4 - 20.9	0 - 49	corn	56	0	none	35	-	Wu et al., 1996a
30 - 387	0 - 29	corn	196	0 - 6	none	19	Fillets had similar protein and ash content, but less fat content than control and no difference in flavor characteristics	Wu et al., 1996b
30 -122.4	19 - 29	corn, soybean meal	103	0 - 6	none	29	-	Wu et al., 1994

Table 9. Summary of published studies evaluating the effects of feeding corn DDGS to Nile tilapia (Oreochromis niloticus), red tilapia and hybrid tilapia (O. aureus × O. niloticus) on growth performance and flesh composition

Fish body weight (initial – final, g)	DDGS %	Ingredients replaced	Trial duration, days	Fishmeal %	Supplemental lysine %	Optimum DDGS %	Flesh composition	Reference
Red tilapia								
31.6 - 265.7	0 - 40	soybean meal, rice bran,hominy feed, meat and bone meal, corn gluten meal	120	0	none	Up to 40	-	Suprayudi et al., 2015
190 - 907	0 - 15	corn, rice bran	120	0	none	Up to 15	No effect	U.S. Grains Council,2006
Hybrid tilapia (O. aureus × O. niloticus)								
6.0 - 81.4 2.1 - 63.2	0 - 50	soybean meal	56(Exp.1) 84(Exp.2)	5	0.0 - 0.27	Up to 30 (Exp. 1) Up to 50 with lysine and lipid supplementation (Exp. 2)	-	Chatvijitkul et al., 2016
3.7 - 63.5	0 - 32	corn,soybean meal	70	8	none	30	-	Welker et al., 2014b
1.5 - 6.1	0 - 40	fish meal, wheat	90	3	0.4	Up to 40	-	U.S. Grains Council, 2007a

meal and corn meal without affecting growth performance, body composition, hematology, immune response and resistance to a Streptococcus iniae infection.

Abo-State et al. (2009) replaced soybean meal with corn DDGS in increments between 0 and 100 percent of the diets, with or without supplemental phytase, and fed these diets to Nile tilapia (2 g initial body weight) for 70 days. They observed the best growth rate and feed conversion in diets containing 0 percent, 25 percent and 50 percent DDGS with phytase.

Schaeffer et al. (2009) conducted two trials to evaluate the use of DDGS in diets for tilapia (35 g initial body weight), and showed that feeding diets containing 0 percent, 17.5 percent, 20 percent, 22.5 percent, 25 percent and 27.5 percent DDGS to partially replace fish meal, resulted in no difference in apparent nutrient digestibility among diets. However, weight gain, feed conversion and protein efficiency ratio (PER) were highest for fish fed the 0 percent DDGS diet, but feeding the 17.5 percent DDGS diet provided better feed conversion and PER. In the second, trial, Nile tilapia were fed 20 percent, 25 percent and 30 percent DDGS diets with or without a probiotic, and no differences were found for weight gain, feed conversion, or PER among dietary treatments. In a subsequent study, Schaeffer et al. (2010) attempted to more narrowly define the optimal diet inclusion rate for juvenile tilapia by determining growth performance responses when feeding diets containing 17.5 to 27.5 percent DDGS. Growth rate was reduced when feeding the DDGS diets containing 5 percent fish meal, compared to the control commercial diet containing 15 percent fish meal. Feeding the diet containing 20 percent DDGS resulted in the best growth performance among the DDGS diets fed. Results from these studies indicate DDGS can be a highly economical feed ingredient in tilapia diets, and can be successfully be used at relatively high dietary inclusion rates if adequate amounts of supplemental amino acids are provided in the diets.

The most definitive study demonstrating the beneficial effects of using DDGS in tilapia diets was recently conducted by Herath et al. (2016). These researchers conducted a 12-week feeding trial to determine the effects of total replacement of fish meal with corn DDGS (52.4 percent), corn protein concentrate (19.4 percent), corn gluten meal (23.5 percent) and high-protein distillers dried grains (HP-DDG; 33.2 percent) on growth performance and body composition in juvenile trout (initial body weight was 4.5 g). Corn co-product diets contained 0.4 to 0.8 percent supplemental L-lysine and 0.3 to 0.4 percent supplemental DL-methionine. Results showed that feeding the 52.4 percent DDGS and control diet provided the highest specific growth rates and survival, followed by feeding the HP-DDG diet compared with other diets (Table 10). Feed conversion, protein efficiency ratio and total amino acid content of the whole body were not affected by dietary ingredients. Protein content in whole body and fillet was highest in fish fed the HP-DDG diet, and lipid content of whole body and fillet were highest in fish fed the DDGS diet. These results show that corn DDGS can effectively replace all of the fish meal in Nile tilapia diets at a level of 50 percent, and support acceptable growth performance, survival, feed utilization and whole body and fillet composition.

Potential Health Benefits from Feeding DDGS

The addition of DDGS to aquaculture diets not only can provide excellent growth performance, survival and flesh composition, but there is increasing evidence it may also provide beneficial effects for improving the immune status and resistance to some diseases in fish. Lim and co-workers (2009) showed that feeding diets containing 40 percent DDGS to channel catfish under a disease challenge with Edwardsiella ictaluri improved resistance, which was likely due to increased total serum immunoglobulins and antibody titers 21 day post-challenge. However, Lim et al. (2007) fed diets containing 40 percent DDGS diets to Nile tilapia (Oreochromis niloticus) challenged with Streptococcus iniae and showed no improvements in hematological and immunological responses. Similarly, Shelby et al. (2008) showed no effect of feeding DDGS on immune function or disease resistance in Nile tilapia. Aydin and Gumus (2016) fed diets containing up to 30 percent DDGS to rainbow trout fry not undergoing a disease challenge and showed no effects on hematological and biochemical responses.

Table 10. Growth performance, survival, protein utilization and whole body and fillet composition of Nile tilapia fed diets containing various corn co-products (adapted from Herath et al., 2016)

Measure	Control	DDGS	Corn protein concentrate	Corn gluten meal	High-protein DDG
Specific growth rate %	3.56^{a}	3.53^{a}	2.63^{d}	2.75^{c}	3.30^{b}
Feed intake, g	84.1^{a}	81.2^{a}	38.8^{b}	40.2^{b}	71.1^{a}
Gain:Feed	1.00	1.05	1.10	1.00	1.05
Survival %	100.0^{a}	97.2^{ab}	75.0^{c}	66.6^{c}	80.6^{bc}
Protein efficiency ratio	3.20	3.06	2.84	3.10	2.99
Protein retention %	49.6^{a}	46.7^{ab}	38.4^{c}	42.0^{bc}	46.2^{ab}
Whole body % wet basis					
Moisture	69.4	69.7	71.6	70.9	68.9
Protein	15.5^{b}	15.4^{b}	13.9^{d}	14.6^{c}	16.7^{a}
Lipid	8.5^{b}	10.0a	9.6^{a}	9.8^{a}	9.9^{a}
Ash	6.9^{a}	5.7^{b}	5.0^{d}	4.0^{e}	5.4^{c}
Fillet % wet basis					
Moisture	78.2	77.2	78.5	77.9	76.2
Protein	18.8^{b}	18.3^{b}	18.7^{b}	19.2^{b}	19.8^{a}
Lipid	1.6^{c}	3.1^{a}	1.9^{bc}	2.2^{b}	2.4^{b}
Ash	1.4	1.3	1.4	1.3	1.2

[a,b,c,d,e] Means within rows with different superscripts are different (P less than 0.05)

Researchers have presumed the factors contributing to the few positive responses reported may be due to the presence of significant amounts of biologically active compounds (mannans, β-glucans and nucleotides) derived from yeast, which comprises about 10 percent of total DDGS mass (Shurson, 2018). Limited data have been published on the levels of these compounds in DDGS, but the β-glucan content of DDGS has been estimated to be about 21.2 percent (Kim et al., 2008). Ringo et al. (2012) reviewed and summarized 14 published studies involving feeding yeast β-glucans to various fish species and reported improvements in pathogen resistance, growth performance and survival.

Extrusion of DDGS diets

In general, the relatively high concentration of fiber in DDGS creates challenges for achieving high pellet durability index in extruded aquaculture diets, especially when added at high dietary concentrations. Researchers have determined the most critical factors affecting extrusion and pellet quality of DDGS diets are die geometry, temperature, moisture content and screw speed. Addition of various binding agents are effective for improving pellet durability and unit density. As a result, acceptable floating feeds containing 60 percent DDGS can be produced under specific conditions to result in feeds that float with unit density values from 0.24 g/cm^3 to 0.61 g/cm^3 and durability values ranging from 96 to 98 percent (Chevanan et al., 2007; 2009). For a more comprehensive review of the effects of extruding aquaculture diets containing DDGS, see Chapter 16.

Conclusions

There is tremendous interest in the global aquaculture industry in using alternative plant-based feed ingredients to replace fish meal in aquaculture diets. As a result, the use of corn DDGS in aquaculture feeds is increasing. Research evaluating optimal diet inclusion rates of DDGS in diets for various aquaculture species is limited but recent studies have shown there are significant opportunities to substantially reduce diet costs while achieving satisfactory growth performance, survival and flesh quality. Dietary DDGS inclusion rates are generally higher for species with a greater ability to use fiber, but vary based on type of ingredients substituted and amounts of other protein sources (e.g. fish meal) included in the diet. Supplemental lysine, methionine and other amino acids may be needed when using high dietary inclusion rates of DDGS to meet digestible amino acid requirements because DDGS contains relatively low concentrations of digestible lysine relative to the requirements, despite having moderately high crude protein content. High protein aquaculture diets may require lower DDGS inclusion rates unless adequate amino acid supplementation is provided. The relatively high lipid content of DDGS may increase whole body fat content in some species, but corn oil in DDGS is relatively low in DHA and contains no EPA. Therefore, ensuring adequate essential fatty acids in aqua feeds can be accomplished by supplementing diets with fish oils. Other benefits of using DDGS in aquaculture feed are to reduce phosphorus excretion due to its relatively high digestible phosphorus content, no concerns about anti-nutritional factors and it may provide immunological benefits. High quality pellets can be produced using the appropriate extrusion conditions. Based upon the results of published research studies, the maximum dietary inclusion rates of DDGS for various aquaculture species is shown in Table 11. While only a few of these studies provided details of the quality and nutritional composition of DDGS sources evaluated, light colored, golden DDGS sources should be used to ensure the highest nutrient digestibility, especially with high dietary inclusion rates.

Table 11. Recommended maximum inclusion rates in diets for various aquaculture species

Species	Maximum dietary DDGS inclusion rate %
Channel catfish	30 to 40 with supplemental synthetic amino acids
Common carp	15
Freshwater prawns	40
Milkfish	45
Pacific white shrimp	40 with supplemental synthetic amino acids
Rainbow trout	50
Red claw crayfish	30
Sunshine bass	10
Tilapia	50 with supplemental synthetic amino acids

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CHAPTER 14

Extruding Aquaculture Diets Containing DDGS

Introduction

EXTRUSION IS THE MOST COMMON THERMAL PROCESS USED TO PRODUCE AQUACULTURE FEEDS, because it improves feed conversion, controls pellet density, provides greater feed stability in water and improves production efficiency and versatility (Khater et al., 2014). Extrusion also results in gelatinization of starch, protein denaturation, hydration, texture alteration, partial dehydration and destruction of microorganisms and toxic compounds (Khater et al., 2014).

Unfortunately, the major challenge with extruding DDGS diets is its inherent low starch and high fiber content (Chin et al., 1989). Reduced starch content of diets reduces expansion during extrusion that affects the physical characteristics, while increased fiber content reduces the mechanical strength and durability of extrudates (Chevanan et al., 2007a).

Extrusion Processes

Extrusion is a process by which a feed or food material is pushed, using a pistonor screw, through an orifice or a die of a given shape. While extrusion is the most common thermal process used to produce aquaculture feeds (Khater et al., 2014), it also has advantages for improving energy and nutrient digestibility in swine (Rojas et al., 2016) and poultry (Lundblad et al., 2011) feeds. Several processes occur during extrusion including fluid flow, heat and mass transfer, mixing, shearing, particle size reduction, melting, texturizing, carmelizing, plasticizing, shaping and forming depending on the material being processed (Camire, 1998). Extrusion has several advantages compared with conventional cooking and steam pelleting processes including: flexibility to make on-line adjustments and achieve desired physical characteristics; manufacture of many types of feed products; has no effluents; is energy efficient; and can be used to process a wide range of materials ranging from dry, highly viscous to moist or wet materials (Maskan and Altan, 2011).

Extruders are available in several designs depending on their application, but are generally classified based on the number of screws. The two general types of extruders are single-screw and twin-screw configurations. Single screw extruders are widely used in the feed industry because of their low initial investment and operating cost compared with twin screw extruders. Single screw extruders operate based on the pressure requirement of the die, slip at the barrel wall and the extent to which the screw is filled, whereas twin screw extruders operate based on the direction the two screws rotate and the extent of intermeshing between the two screws (Chevanan et al., 2005). Single-screw extruders consist of a single rotating screw in a metal barrel, which can be configured in many patterns. The three main components of the single-screw extrusion process consist of the feeder, transition and compression and metering stages. In this design, ground feed or ingredients enter the hopper, and the rotating action of the screw conveys the feed material to the transition section where the screw channel becomes more narrow and compacted. The mechanical energy causing compaction generates heat, which is dissipated to increase the temperature of the material, resulting in gelatinization of starch and cohesion. As the feed material continues to be transported by the metering section, it is pushed through the die opening. Twin screw extruders differ from single screw extruders and have several advantages including: no pre-conditioning, self-cleaning, greater range in length to diameter ratios; good mixing; shorter residence time and good heat transfer; and capable of handling a wide range in moisture content and types of feed ingredients (Harper, 1989).

Factors Affecting Extrusion of Aquaculture Feeds

Many forms of fish feed are produced including extruded-floating, extruded non-floating, steam pelleted, large crumbles, small crumbles and coarse meal, and steam pelleting and extrusion are the two primary methods of manufacturing fish feeds. Most fish require floating pellets, or they can at least be trained to accept floating pellets, whereas shrimp need sinking pellets (Craig, 2009). Steam pelleting is generally used to produce dense pellets that sink rapidly in water. Extrusion is generally used to produce floating pellets, and has several advantages compared with steam pelleting including: continuous, high throughput processing; processes feeds with a wide range in moisture content; energy efficiency; capability of processing dry, viscous feed components; improves texture and flavor characteristics; minimizes thermal changes during processing; results in feeds more stable in water and float on the water surfaces; and is applicable for unconventional ingredients (Chevanan et al., 2005; Brown et al., 2012).

Several factors affect the efficiency of manufacturing and quality characteristics of extruded fish feeds including: nutrient composition (protein, lipid, fiber and ash content); moisture content; particle size distribution; feed throughput; type of screw, screw speed and screw configuration; and temperature (Chevanan et al., 2005). Important measurements of the quality of extruded fish feeds are: apparent and true bulk density, porosity, moisture content, pellet durability, structural integrity, water stability index, water absorption index and buoyancy, but there are no standard methods to evaluate these properties (Chevanan et al., 2005). While nutrient composition of diets is important for producing high quality extruded aquaculture diets, it was not extensively studied before 2011, until Kannadhason et al. (2011) showed that protein content was an important factor in extrudate quality.

Feed ingredient properties that have the greatest effect on extrusion are moisture content, particle size and chemical composition. Starch is useful because of its ability to create expansion and cohesiveness, whereas fiber reduces expansion, cohesiveness, durability and water stability (Brown et al., 2012). Extrusion of high protein ingredients and feeds results in limited expansion and more porous and textured final extrudates, and feeds high in lipid content reduce starch gelatinization and expansion because they act as lubricants (Brown et al., 2012).

Extruding Aquaculture Feeds Containing DDGS

The feed ingredient properties that have the greatest effect on extrusion are moisture content, particle size, and chemical composition. Chemical composition of DDGS continues 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 and extrudate 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 when manufacturing high quality extruded aquaculture feeds containing high dietary inclusion rates of DDGS, because these chemical components have negative effects on achieving the desired pellet durability index (PDI). Therefore, binding agents must be added to achieve greater PDI in extruded fish feeds containing DDGS. Table 2 provides a summary of various binding agents, their typical diet inclusion rates, and characteristics for use in aquaculture feeds.

Several studies have been conducted to evaluate various quality characteristics of extruded fish feeds containing various concentrations of DDGS and are summarized in Table 3. Nine studies have evaluated the use of single screw extruders and five studies used twin screw extruders. While many physical and chemical characteristics of diets were reported in these studies, ingredient composition, type of binder used, DDGS inclusion rate, were included along with unit density and pellet durability index (PDI), because these are major factors contributing to quality aquaculture feeds. In general, including DDGS in these formulations created challenges, particularly at high-diet inclusion rates, but the addition of various binding materials generally improved unit density and PDI. Most diets evaluated in these studies, except for those reported by Chevanan et al. (2009) and Rosentrater et al. (2009b), had extruded DDGS diets with unit densities less than 1.0 g/cm^3, which indicates they floated. Furthermore, pellet durability index of extruded diets in the majority of studies was greater than 85 percent in diets containing up to 60 percent DDGS, and only two studies (Chevannan et al., 2008; Kannadhason et al., 2011) reported decreases in PDI as dietary DDGS inclusion rates increased. Specifically, Chevanan et al. (2007b) showed that high-quality (high PDI and low unit density) pellets can be produced when adding 60 percent DDGS to a corn, soy, fish meal diet using whey as a binder. Kannadhason et al. (2011) evaluated the effects of various starch sources with various proportions of DDGS and protein on various physical properties of single screw extrudates and found increasing the levels of DDGS and protein led to an increase in unit density and pellet durability. Increasing moisture content generally increases PDI, but decreases unit density. Increasing die temperature decreases PDI and unit density, but increasing the L:D slightly improves these pellet quality indicators. Therefore, acceptable extruded fish feeds, containing relatively high concentrations of DDGS and a pellet binder (whey or starch), can be produced by properly managing moisture content, die temperature and L:D of the die during the extrusion process.

Hiltonet al. (1981) evaluated the effects of both extrusion processing and steam pelleting on pellet durability, water absorption and physiological response of trout. They determined extruded pellets absorbed more water, had better water stability and were more durable than the steam pellets.

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

Table 2. Common binding agents used in steam pelleted aquaculture feeds (adapted from Lovell, 1989)

Binding agent	Amount added to diets %	Comments
Carboxymethylcellulose	0.5 to 2.0	Good binder but expensive
Alginates	0.8 to 3.0	Good binder in moist feeds and must combine with divalent or polyvalent cations to be effective
Polymethylocarbamide	0.5 to 0.8	Very good binder, not approved by U.S. FDA, and unpalatable for some fish
Guar gum	1.0 to 2.0	Good binder but expensive
Hemicellulose	2.0 to 3.0	Moderate binder at a moderate cost
Lignin sulfonate	2.0 to 4.0	Good binder at a moderate cost
Sodium and calcium bentonite	2.0 to 3.0	Less effective than organic binders
Molasses	2.0 to 3.0	Moderate binder with nutritional value
Whey	1.0 to 3.0	Moderate binder with nutritional value
Gelatinized starches from corn, potato, sorghum, rice, and cassava	10 to 20	Good binders with nutritional value but must be added at high diet inclusion rates to be effective
Wheat gluten	2.0 to 4.0	Good binder but expensive

Table 3. Summary of extrusion type, diet composition, binder, DDGS concentration of extruded aquaculture feeds on unit density and pellet durability index of extruded feeds

Extrusion type Reference Fish species, if applicable	Diet Composition	Binder	DDGS %	Unit Density, g/cm3	PDI %
Single screw extrusion					
Chevannan et al. (2008)	Soy flour, corn flour, fish meal, mineral and vitamin premix	None	20	0.96	89
			30	0.93	65
			40	0.93	56
Chevanan et al. (2009)	Soy flour, corn flour, fish meal, mineral and vitamin premix	Whey	20	1.05	94
			30	1.07	94
			40	1.06	94
Chevanan et al. (2007a)	Soy flour, corn flour, fish meal, mineral and vitamin premix	Whey	40	0.88 – 1.03	85 – 98
Kannadhason et al. (2011) Tilapia and channel catfish	Soy flour, fish meal, whey, mineral and vitamin premix	Cassava starch	20	0.78	82
			30	0.88	84
			40	0.86	86
		Corn starch	20	0.90	85
			30	0.94	76
			40	0.91	63
		Potato starch	20	0.79	82
			30	0.88	85
			40	0.90	87
Rosentrater et al. (2009a) Tilapia	Corn starch, soybean meal, fish meal, whey, mineral and vitamin premix	Corn starch	20	1.03	71
			25	1.01	91
			30	1.02	70
Kannadhason et al. (2009) Tilapia	Soybean meal, fish meal, whey, mineral and vitamin premix	Tapioca starch	20	0.94	90
			25	0.93	96
			30	0.99	84
Rosentrater et al. (2009b) Tilapia	Soybean meal, fish meal, whey, mineral and vitamin premix	Potato starch	20	0.85	89
			25	0.97	96
			30	0.93	82
Ayadi et al. (2013) Nile tilapia	Corn flour, fish meal, 30, 40, or 50 percent soybean meal and mineral vitamin premix	Whey	20	0.97	94
			30	0.89	95
			40	0.90	95
Ayadi et al. (2016) Juvenile Nile tilapia	Soybean meal, corn, fishmeal, whey, mineral and vitamin premix	70 percent amylose 30 percent amylopectin	20	0.97	93
		100 percent amylopectin	20	0.99	94

Table 3. Summary of extrusion type, diet composition, binder, DDGS concentration of extruded aquaculture feeds on unit density and pellet durability index of extruded feeds

Extrusion type Reference Fish species, if applicable	Diet Composition	Binder	DDGS %	Unit Density, g/cm3	PDI %
Twin screw extrusion					
Chevanan et al. (2007b)	Soy flour, corn flour, fish meal, mineral and vitamin premix	Whey	20	0.24	98
			40	0.34	98
			60	0.61	97
Kannadhason et al. (2010) Tilapia	Soybean meal, corn, fish meal, soybean oil, mineral and vitamin premix	Whey	0	0.73	93
			17.5	0.90	97
			20	1.00	97
			22.5	0.88	95
			25	0.87	97
			27.5	0.92	93
Ayadi et al. (2011) Rainbow trout	Fishmeal, corn gluten meal, whole wheat flour, menhaden oil, Celufil, mineral and vitamin premix	None	0	0.93	83
			10	0.89	91
			20	0.89	89
			30	0.94	88
			40	0.97	92
			50	0.99	95
Fallahi et al. (2011) Nile tilapia	Soybean meal, corn flour, fish meal, soybean oil, mineral and vitamin premix	Whey	20	0.92 – 1.02	94 – 99
Fallahi et al. (2012) Yellow perch	High protein DDG, fish meal, corn gluten meal, whole wheat flour, oils, crystalline amino acids, mineral and vitamin premix	Carboxymethylcellulose	31	0.66	99
	As above + fermented high protein soybean meal		31	0.60	99
	As above + soy protein concentrate		31	0.50	99

In summary, there are significant economic advantages of using high-diet inclusion rates of DDGS in aquaculture diets, but achieving desired PDI often limits DDGS use in commercial feed mills. Several scientific studies have evaluated the use of various pellet binder, single vs. twin screw extrusion processes and dietary DDGS inclusion rates on unit density and PDI of extrudates. There are numerous interactions among extruding variables that contribute to inconsistent PDI values, but several studies have demonstrated adequate unit density and PDI can be achieved when extruding DDGS diets. More research is needed to optimize chemical composition of aquaculture diets containing DDGS for various aquaculture species.

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CHAPTER 15

Reduced-Oil DDGS in Beef Cattle Diets

Introduction

THE U.S. BEEF CATTLE INDUSTRY has been a major consumer of wet and dried corn distillers co-products for decades. In 2017, the U.S. beef industry was the greatest consumer of distillers co-products amount all animal species, which represent 44 percent of total domestic use. As a result, there has been a significant amount of research conducted to evaluate the feeding value of corn distillers co-products to beef cattle, of which most has focused on optimizing use in finishing feedlot beef cattle where it is used in the greatest quantities. Several excellent research summaries and feeding recommendations were been published 10 or more years ago (Erickson et al., 2005; Tjardes and Wright, 2002; Loy et al., 2005a; Loy et al., 2005b, Klopfenstein et al. (2008)). However, over 140 studies have been published since 2010 and the results of these studies are summarized in this chapter.

Energy, Nutrient Composition and Digestibility of Corn Distillers Co-Products Beef Cattle

Corn DDGS is used as both a high-energy and mid-protein feed ingredient in beef cattle diets. A detailed summary of the averages and ranges of DDGS nutrient composition is provided in Chapter 4 of this handbook. In the U.S., finishing beef cattle have successfully been fed as much as 40 percent DDGS of ration dry matter as a replacement for corn grain. However, when adding more than 30 percent corn DDGS to the diet for use primarily as an energy source, it provides more protein and phosphorus than required for finishing feedlot cattle.

Energy

The primary carbohydrate fraction in DDGS is NDF (neutral detergent fiber). Much of the NDF in DDGS is obtained from the pericarp (bran) portion of the corn kernel which contains about 69 percent NDF, and is highly (87 percent) and rapidly (6.2 percent per hour) digested (DeHaan et al., 1983). Because of the highly digestible and rapidly fermentable fiber in DDGS, it is frequently used as a high energy and protein source in diets for feedlot finishing cattle.

The corn oil present in DDGS is also a significant contributor to its energy content. Vander Pol et al. (2007) showed the digestibility of corn oil was 70 percent. However, as the level of fatty acid intake increases, fatty acid digestion decreases (Plascencia et al., 2003), which likely explains the decline in feeding value of DDGS when fed at high (greater than 30 percent) levels of the diet.

Initial studies indicated that the NE_{gain} of corn DDGS for beef cattle was 21 percent greater than the NE value of dry-rolled corn (Ham et al., 1994). A subsequent review by Tjardes and Wright (2002) indicated corn DDGS contains 2.16 to 2.21 Mcal/kg of NE_m and 1.50 to 1.54 Mcal/kg of NE_g among sources. In fact, many ruminant nutritionists prefer using corn DDGS instead of corn grain for finishing feedlot cattle because it contains 118 to 130 percent of the energy value of corn, and due to its low starch and readily fermentable fiber content, feeding high amounts reduces the risk of rumen acidosis compared with feeding dry-rolled corn (Ahern et al., 2011).

Unfortunately, there are limited data on the energy content of reduced-oil DDGS for beef cattle. Bremer (2014) determined the energy value of reduced-oil (7.2 percent crude fat) and high-oil (12.0 percent crude fat) modified wet DDGS with solubles when fed at 20 or 40 percent of dry matter intake to growing calves and showed no difference in energy content between the reduced-oil and high-oil modified wet DDGS with solubles sources. They estimated the energy value of these two DDGS sources was about 124 percent of the energy value of corn grain. However, when these sources of modified DDGS with solubles were fed to finishing cattle, the reduced-oil DDGS source had about 89 percent of the feeding value of high-oil DDGS, but feeding the reduced-oil modified wet distillers source improved gain:feed with increasing diet inclusion rates.

DDGS reduces acidosis

Feeding diets containing DDGS reduces acidosis in feedlot cattle fed high-grain diets. Subacute acidosis is often a problem when finishing cattle are fed high-grain diets because corn grain contains a high amount of rapidly fermentable starch. However, the starch content in DDGS is low (two to 5 percent), while the fiber, protein and fat content are relatively high allowing the amount of forage in the diet to be reduced when feeding diets containing more than 20 percent DDGS of dry matter intake. Furthermore, low-quality forages can be used effectively in diets that contain greater than 20 percent DDGS because of its high protein content (Klopfenstein et al., 2008).

Protein

Corn DDGS is relatively high in protein (27 to 30 percent) content, and historically has also been used as a protein supplement in feedlot cattle diets (Klopfenstein et al., 2008). Most of the protein in corn DDGS is zein, which has a high rumen escape value (Little et al., 1968), and about 40 percent of zein is degraded in the rumen (McDonald, 1954). Although rumen bypass protein has been shown to be quite variable among DDGS sources (Aines et al., 1987), protein in DDGS has 1.8 times greater protein value than protein in soybean meal.

Corn DDGS is high in rumen undegradable protein (RUP). Acid detergent insoluble nitrogen (ADIN) can be used to determine the extent of protein damage of DDGS, and once this ADIN value is determined in the laboratory, it can be multiplied by a factor of 6.25 to estimate the amount of crude protein in DDGS that is unavailable and can be compared to the actual crude protein value to determine the extent of protein damage. The proportion of bypass protein (RUP) in DDGS is approximately 60 to 70 percent compared with 30 percent for soybean meal. However, Erickson et al. (2005) indicated the high bypass protein value of DDGS is due to the innate characteristics of the protein rather than drying or moisture content, and does not appear to be influenced by ADIN since protein efficiency (kg gain/kg supplemental protein) appears to stay the same, or increase as the amount of ADIN in DDGS increases.

Limited studies have been conducted to determine RUP protein content of DDGS in beef cattle. Castillo-Lopez (2013) determined the RUP content, as a percentage of crude protein, was about 63 percent. Feeding DDGS tended to decrease duodenal bacterial protein supply, had no effect on duodenal protozoa crude protein, and provide a small amount of yeast crude protein.

Li et al. (2012) compared wheat, corn, wheat DDGS, high-oil (11.5 percent crude fat) corn DDGS and reduced-oil (4.5 percent crude fat) DDGS on in situ and in vitro degradability of crude protein and amino acids. They estimated the true digestibility of dietary protein was 98.5, 96.5, 94.3, 93.5 and 88.9 percent for wheat, corn, wheat DDGS, high-oil corn DDGS and reduced-oil corn DDGS, respectively. These researchers concluded ruminal degradation of crude protein in DDGS was less than in the original grain, and lower for reduced-oil corn DDGS than high-oil corn DDGS, but not different between wheat DDGS and corn DDGS. Ruminal degradation of essential amino acids was greatest for wheat DDGS, followed by high-oil corn DDGS and reduced-oil corn DDGS. Although the protein quality and essential amino acids in RUP was slightly less than the original grains, all of these sources are excellent sources of RUP. In a subsequent study, Li et al. (2013) showed that wheat DDGS and reduced-oil (4.5 percent crude fat) corn DDGS, when supplemented in backgrounding cattle diets, provided greater amounts of crude protein and amino acids in the small intestine, compared with feeding canola meal and high-oil DDGS when diets were formulated on an isonitogenous basis.

Urea

When cattle diets contain high amounts of rapidly fermentable carbohydrates (e.g. corn grain) and a high proportion of the dietary crude protein is derived from corn, a deficit in degradable protein intake may occur. Ceconi et al. (2015) conducted two experiments to evaluate the effect of increasing intake of degradable protein and the addition of urea on feedlot cattle growth performance, carcass characteristics, rumen fermentation, total tract digestibility and purine derivatives-to-creatinine index. Results from this study showed that due to limited degradable protein intake from feeding dry-rolled corn and high-moisture corn diets containing 20 percent DDGS, urea supplementation was necessary to improve ruminal fermentation, feed digestibility and growth performance.

Phosphorus

Corn DDGS is low in calcium but relatively high in phosphorus (P) and sulfur content. Depending upon the feeding level, adding distiller's grains to the diet may allow complete removal of other supplemental phosphorus sources from the mineral mixture previously fed. Due to the high levels of DDGS fed, beef cattle feedlot diets contain excess phosphorus relative to their requirement. This results in excess phosphorus being excreted in manure, and must be considered when developing manure management plans to prevent unwanted environmental pollution. Due to the low calcium level of DDGS, supplemental calcium sources (e.g. ground limestone or alfalfa) must be added to the diet to maintain a calcium to phosphorus ratio between 1.2:1 to no more than 7:1 to avoid reductions in animal performance and urinary calculi (Tjardes and Wright, 2002).

Geisert et al. (2010) fed diets containing brewers grits to provide low phosphorus (0.12 percent P), medium phosphorus (0.27 percent) and high phosphorus (0.42 percent P) with supplemental monosodium phosphate, dry-rolled corn and 30 percent DDGS, to determine phosphorus digestibility and excretion. Results from this study showed that adding 30 percent DDGS to the diet results in relatively high total phosphorus content and intake, and it is about 50 percent digestible (Table 1). However, the amount of digestible phosphorus in DDGS exceeds the phosphorus requirement for finishing cattle and results in a significant amount of total phosphorus excretion (about 54 percent of intake). The phosphorus requirement for finishing cattle is less than the phosphorus content of typical U.S. beef cattle feedlot diets (0.30 to 0.50 percent) and NRC (2001) estimates. Therefore, the addition of supplemental phosphorus to a typical corn-based or DDGS-based diet is unnecessary because the phosphorus requirement for maximum growth performance is less than 0.17 percent of diet dry matter. By eliminating excess phosphorus provided by mineral supplements from

Table 1. Phosphorus intake, apparent digestibility and excretion from beef steers fed different amounts and source of dietary phosphorus (adapted from Geisert et al. 2010)

	Low P	Medium P	High P	Dry-rolled corn	DDGS
Diet phosphorus %	0.12	0.27	0.42	0.30	0.36
Dry matter intake, kg/day	8.86	10.54	9.76	9.57	9.48
Dry matter digestibility %	71.9	69.6	72.5	75.7	68.5
P intake, g/day	11.0^{a}	28.0^{b}	41.3^{d}	28.9^{b}	34.0^{c}
Apparent phosphorus digestibility %	11.3^{a}	48.9^{b}	39.0^{b}	58.6^{b}	51.5^{b}
Fecal phosphorus excreted, g/day	9.3^{a}	14.2^{a}	26.0^{b}	12.1^{a}	15.9^{a}
Urine phosphorus excreted, g/day	0.4^{a}	2.2^{b}	1.9^{b}	2.0^{b}	2.3^{b}
Total phosphorus excreted, g/day	9.7^{a}	16.3^{ab}	27.9^{c}	14.0^{ab}	18.2^{b}
% excreted in urine as percent of total phosphorus excreted	3.5	14.2	9.9	14.3	12.4

^{a,b,c,d}Means within row without the same superscript are different (P less than 0.10).

feedlot cattle diets, the amount of phosphorus excretion in manure will be reduced to minimize the risk of negative environmental consequences.

High diet inclusion rates of DDGS increases nitrogen and phosphorus excretion in manure

When DDGS is used as an energy source and added to the diet at levels greater than 15 to 20 percent, excess protein and phosphorus are fed. The excess protein is used for energy that occurs through deamination of amino acids and results in urea excretion. Vander Pol et al. (2005) showed when finishing cattle are fed diets containing 10 or 20 percent DDGS of diet dry matter, there is no benefit for supplementing diets with urea, suggesting nitrogen recycling was occurring. However, Erickson et al. (2005) suggested NRC (2001) guidelines should be followed for degradable intake protein supplementation when formulating diets containing less than 20 percent DDGS. Feeding excess phosphorus provided by DDGS in feedlot cattle diets does not appear to have any negative effects on performance or carcass traits if adequate calcium is supplemented to the diets to maintain an acceptable calcium to phosphorus ratio.

Sulfur

High levels of sulfur in DDGS can be a concern for beef feedlot cattle (Lonergan et al. 2001), and Chapter 14 provides a more detailed summary of managing sulfur intake in ruminants. Ethanol plants use sulfuric acid to adjust pH during ethanol and DDGS production. As a result, sulfur content of DDGS can be highly variable and range from 0.6 to 1.0 percent. Adequate dietary sulfur is required by microorganisms in the rumen, but too much sulfur in the diet can cause polioencephalomalcia, reduce dry matter intake, ADG and liver copper levels. Felix et al. (2012a) indicated that when greater than 30 percent DDGS is included in the ruminant diet, dry matter intake, rumen pH and fiber digestibility in beef cattle may be reduced when it comprises the majority of the diet dry matter). An increase in rumen pH to 6.35 can increase dry matter intake and improve ruminal digestibility of nutrients (Leventini et al., 1990). Therefore, adding alkaline supplements to high-DDGS diets may be effective in increasing pH and improving nutrient digestibility and several studies have been conducted to evaluate the effects of thiamine, copper, NaOH and CaO in high sulfur diets containing DDGS.

Neville et al. (2012) evaluated the effects of feeding 20, 40 or 60 percent DDGS diets and corn processing method (high-moisture corn vs. dry-rolled corn) on growth performance, incidence of polioencephalomalacia and concentrations of hydrogen sulfide gas in feedlot steers. Diets contained 0.6 to 0.9 percent sulfur, and were supplemented with thiamine to provide 150 mg/animal/day. Carcass-adjusted final body weight decreased linearly with increasing concentrations of DDGS in the diet, but carcass adjusted gain:feed was not affected. Hot carcass weight and backfat were reduced when feeding increasing levels of DDGS resulting in decreased yield grade. Hydrogen sulfide gas increased with increasing concentration of DDGS in the diet but there were no confirmed cases of polioencephalomalacia. Corn processing method did not affect growth performance, incidence of polioencephalomalacia, or hydrogen sulfide gas concentrations in the rumen. These results, as well as those reported by Neville et al. (2010) and Schauer et al. (2008) have consistently demonstrated sulfur from DDGS can be fed in excess of the maximum tolerable level in both lambs and steers fed high concentrate diets. It is possible the maximum tolerable level of sulfur reported in NRC (2005) needs to be re-evaluated.

Copper supplementation in DDGS-based diets may be effective in reducing rumen hydrogen sulfide production and prevent sulfur toxicity when high amounts of DDGS containing high sulfur content is fed. In the rumen, copper and sulfur can precipitate and form copper sulfides, which reduce the availability of both copper and sulfur to the animal (McDowell, 2003). The maximum tolerable level of copper in beef cattle diets has been reported to be 100 mg/kg diet dry matter (McDowell, 2003). Therefore, Felix et al. (2012a) evaluated the effects of supplementing 60 percent DDGS diets with 0, 100 or 200 mg Cu/kg diet dry matter on growth performance, carcass characteristics and rumen sulfur metabolism in growing beef heifers and steers. Results showed that although supplemental copper improved feed efficiency of cattle consuming 60 percent DDGS diets, and had no effect on ADG or carcass characteristics, the effects of copper supplementation on rumen sulfur metabolism were minimal, even when supplemented at twice the recommended maximum tolerable limit for beef cattle.

Because reduced rumen pH interferes with fiber fermentation, and DDGS has a relatively high-fiber content and relatively low pH, there have been several research studies to determine the effects on using alkaline treatments or supplements to increase rumen pH and fiber digestibility. Felix et al. (2012b) showed cattle fed 25 to 60 percent DDGS diets treated with 2 percent NaOH prior to feeding, increased in situ NDF disappearance compared with cattle fed DDGS diets with no NaOH treatment. Treating DDGS with 2 percent NaOH may increase rumen pH and decrease hydrogen sulfide concentrations to reduce the risk of polioencephalomalacia, and adding NaOH was effective in neutralizing the acidity from sulfuric acid in DDGS. However excess Na in ruminant diets can reduce feed intake (Croom et al., 1982), and the optimal inclusion of alkaline treatment to reduce the acid effects of DDGS-based diets to improve growth performance has not been determined. Therefore, Frietas et al. (2016) conducted a study to determine the optimal diet inclusion rate of NaOH in 50 percent DDGS-based diets to improve growth performance, carcass characteristics and feed intake patterns of feedlot steers. However, due to the low pH (5.5) of the DDGS source fed in this study, there was no effect of adding up to 1.5 percent NaOH to DDGS diets on growth performance or carcass characteristics.

Increased feeding value and growth performance may be achieved when feeding more than 30 percent DDGS diets by adding calcium oxide because treating DDGS with alkaline agents before feeding improves nutrient digestibility (Felix et al., 2012b). Schroeder et al. (2014) conducted a study to determine the effects of feeding 50 percent DDGS diets with or without supplemental calcium oxide on growth performance, carcass characteristics, diet digestibility, pattern of feed intake and meal distribution. Results from this study showed steers fed calcium oxide-treated DDGS had decreased dry matter intake, but had no effect on ADG, which resulted in an improvement in gain:feed compared with steers not fed calcium-oxide. Steers fed the calcium oxide-treated DDGS ate a similar number of meals but the amount consumed in each meal was less than those fed DDGS without CaO treatment. Although CaO treatment of DDGS improved feed efficiency, it had no effect of dry matter or NDF digestibility. In contrast, Nuñez et al. (2014) evaluated the addition of calcium oxide to 60 percent DDGS diets fed to feedlot steers on ruminal fermentation, diet digestibility, growth performance and carcass characteristics of feedlot steers. Their results showed that adding up to 1.6 percent CaO was effective in improving growth performance fiber digestibility, volatile fatty acid production, amino acid utilization, metabolic acid-base balance and carcass dressing percentage, while minimizing rumen pH variation in feedlot cattle fed 60 percent DDGS diets.

If more than 0.4 percent sulfur from feed (dry matter basis) and water is consumed, polioencephalomalacia in cattle can occur. Furthermore, sulfur interferes with copper absorption and metabolism, which is further reduced in the presence of molybdenum. Therefore, in geographic regions where high sulfur levels are found in forages and water, the level of DDGS that can be added may need to be reduced (Tjardes and Wright, 2002). Drewnoski et al. (2014) indicated the risk of sulfur toxicity can be minimized when feeding high dietary inclusion rates of DDGS with high-sulfur content to cattle by providing at least 7 to 8 percent NDF from a forage source in diets containing more than 0.4 percent total sulfur. Table 2 can be used as a guide to determine maximum diet inclusion rates of DDGS with variable sulfur content for finishing feedlot cattle to avoid the risk of sulfur toxicity and the occurrence of polioencephalomalacia.

Feeding DDGS to Finishing Cattle

Feeding wet and DDGS to beef cattle is perhaps the most extensively researched among all animal species. As one of many examples, Buckner et al. (2007) conducted a study to evaluate the effects of feeding increasing levels of DDGS to finishing steers on growth performance and carcass characteristics (Table 3). Results from this study showed no effect of increasing levels of DDGS on dry matter intake, twelth rib fat depth, loin muscle area and marbling score, but there was a quadratic effect in ADG and hot carcass weight, and a quadratic trend for gain:feed. Furthermore, the feeding value of DDGS is greater than corn at all of the diet inclusion rates evaluated, but declines with increasing dietary inclusion rates (Table 3). Klopfenstein et al. (2008) used the Buckner et al. (2007) data, along with results from four other experiments in their meta-analysis. Their results also showed a quadratic response to ADG when increasing levels of DDGS were fed, but observed a cubic response in gain:feed. Results from the meta-analysis showed maximum ADG is achieved when including 20 to 30 percent DDGS in the diet, and maximum gain:feed is achieved by feeding 10 to 20 percent DDGS diets for finishing cattle.

Table 2. Range in dietary sulfur[1] in corn-based beef cattle finishing rations assuming 10 percent variation from among loads of DDGS (adapted from Drewnoski et al., 2014)

	DDGS inclusion rate %				
	20	30	40	50	60
Sulfur in DDGS %	Dietary S %				
0.3	0.16 – 0.17	0.18 – 0.18	0.20 – 0.21	0.22 – 0.23	0.23 – 0.25
0.4	0.18 – 0.19	0.21 – 0.22	0.24 – 0.25	0.27 – 0.29	0.29 – 0.32
0.5	0.20 – 0.21	0.24 – 0.27	0.28 – 0.30	0.32 – 0.34	0.35 – 0.38
0.6	0.22 – 0.24	0.26 – 0.30	0.32 – 0.34	0.37 – 0.40	0.41 – 0.45
0.7	0.24 – 0.26	0.28 – 0.33	0.36 – 0.39	0.42 – 0.45	0.47 – 0.51
0.8	0.26 – 0.28	0.33 – 0.35	0.40 – 0.43	0.52 – 0.56	0.53 – 0.58
0.9	0.28 – 0.30	0.36 – 0.38	0.44 – 0.47	0.52 – 0.56	0.59 – 0.65
1.0	0.30 – 0.32	0.39 – 0.41	0.48 – 0.52	0.57 – 0.62	0.65 – 0.71

[1]Assumes no sulfur is obtained from drinking water and that other diet ingredients contain 0.13 percent sulfur.

Table 3. Growth performance and carcass characteristics of finishing beef steers fed increasing levels of DDGS in the diet (adapted from Buckner et al., 2007)

Response criteria	0% DDGS	10% DDGS	20% DDGS	30% DDGS	40% DDGS
Dry matter intake, kg/d	9.25	9.47	9.52	9.71	9.47
ADG, kg	1.50	1.61	1.68	1.62	1.59
Gain:Feed	0.162	0.171	0.177	0.168	0.168
Feeding value[1]	100	156	146	112	109
Hot carcass wt., kg	351	362	370	364	359
12th rib fat, cm	1.42	1.37	1.50	1.40	1.47
Loin muscle area, cm^2	80.0	80.6	82.6	81.3	81.3
Marbling score[2]	533	537	559	527	525

[1]Value relative to corn calculated by difference in Gain:Feed divided by DDGS dietary inclusion rate.

[2]Marbling score of 400 = slight0, 500 = small0

Another recent example of the positive benefits of feeding high dietary inclusion rates (up to 40 percent) of DDGS to finishing beef cattle, was conducted by Swanson et al. (2014). In this study, researchers fed diets containing 20 or 40 percent DDGS with coarse or finely ground corn to yearling steers to determine the effects on growth performance and carcass traits. Final body weight and ADG were not affected by DDGS inclusion rate or corn particle size, but dry matter intake decreased and gain:feed increased with increasing DDGS inclusion rate (Table 4). Carcass traits were not affected by DDGS inclusion rate or dry-rolled corn particle size. These results show that up to 40 percent DDGS can be fed to finishing cattle to improve ADG and gain:feed without affecting carcass quality.

Several studies (n = 28) have been conducted since the meta-analysis conducted by Klopfenstein et al. (2008), and a summary of these studies is shown in Table 5. Unfortunately, the crude fat content of the DDGS sources used were not reported for the majority of these studies, but is indicated in the summary if this information was available. Studies by Frietas et al. (2017), Engle et al. (2016), Rodenhuis et al. (2016), Nuñez et al. (2015), Gigax et al. (2011) and Leupp et al. (2009) reported using reduced-oil wet or DDGS in finishing beef cattle studies. In the study by Gigax et al. (2011), diets containing dry-rolled and high moisture corn with 35 percent dry matter of wet DDGS with solubles (WDGS) containing reduced-oil (6.7 percent) or high-oil (12.9 percent) crude fat were fed to finishing steers. Cattle fed the high-oil WDGS

Table 4. Effects of feeding fine and coarse dry-rolled corn and 20 or 40 percent DDGS diets on growth performance and carcass characteristics of finishing cattle (adapted from Swanson et al., 2014)

	Dry-rolled corn processing			
	Coarse (2.68 mm)		Fine (1.46 mm)	
Measure	20% DDGS	40% DDGS	20% DDGS	40% DDGS
Initial body weight, kg	345	345	343	345
Final body weight, kg	606	607	600	603
ADG, kg/day	2.06	2.05	2.01	2.03
Dry matter intake, kg/day[1]	12.1	11.0	11.6	11.0
Dry matter intake % of body weight/day[1]	2.55	2.31	2.47	2.31
Gain:Feed[1]	0.169	0.185	0.169	0.178
Hot carcass weight, kg	361	369	360	360
12th rib fat thickness, cm	1.06	1.37	1.27	1.28
Loin muscle area, cm^2	82.2	82.0	81.3	83.3
Marbling score[2]	543	538	533	530

[1] Effect of DDGS inclusion rate (P less than 0.001)

[2] Marbling score = 500 for modest and 600 for moderate marbling

had increased ADG, final body weight and hot carcass weight compared with steers fed the corn or reduced-oil WDGS diets, but steers fed the reduced-oil WDGS diet had similar dry matter intake, ADG and gain:feed as cattle fed the corn control diet. These results suggest that feeding 35 percent reduced-oil WDGS provides at least equal growth performance and carcass composition as feeding dry-rolled and high moisture corn diets to finishing steers.

It is interesting to note many of these recent studies evaluated very high (50 to 70 percent) diet inclusion rates of DDGS, and depending on the diet formulation and feeding conditions, a few reported good growth performance and carcass characteristics. Furthermore, several studies routinely used 20 to 25 percent DDGS diets as control diets, which suggests there is a high degree of confidence among nutritionists that acceptable growth performance and carcass characteristics are consistently achieved when feeding diets containing up to 25 percent DDGS to feedlot cattle. Therefore, there is no reason why similar and relatively high diet inclusion rates of DDGS should not be used in other countries.

Table 5. Summary of 28 published studies evaluating growth performance and carcass characteristic responses[1] of finishing beef cattle fed various types of DDGS diets since 2009

Growth phase, initial BW	DDGS inclusion; crude fat content	Feeding conditions	Growth Responses	Carcass Responses	Reference
Finishing cattle					
Steers, 211-261 kg	50 percent; 8.8 percent crude fat	Diets contained 20 percent corn silage, 20 percent dry-rolled corn, and 50 percent DDGS with 0, 0.5, 1.0, or 1.5 percent NaOH	No effects of NaOH supplementation on final BW, ADG, and gain:feed	No effects of NaOH level on HCW, LM are, carcass yield, backfat thickness, or marbling	Frietas et al., 2017
Steers, 310 kg	26 percent grower and finisher; 5.8 or 9.6 percent crude fat	Grower diets contained 19 percent grass hay, 22 percent corn silage, 30 percent corn or barley, 3 percent supplement; Finisher diets contained 20 percent corn silage, 51 percent corn or barley, 3 percent supplement	No differences in ADG, DMI, and Gain:Feed	No difference in carcass dressing percentage, HCW, YG, LM area, marbling score, and backfat	Engle et al., 2016

Table 5. Summary of 28 published studies evaluating growth performance and carcass characteristic responses[1] of finishing beef cattle fed various types of DDGS diets since 2009

Growth phase, initial BW	DDGS inclusion; crude fat content	Feeding conditions	Growth Responses	Carcass Responses	Reference
Steers, 436 kg	20, 40, or 60 percent DDGS; 10 percent crude fat	Diets contained increasing amounts of DDGS to replace dry-rolled corn and 300 mg ferric Fe/kg from ferric ammonium citrate (FAC) and contained 0.28, 0.41, 0.56 percent sulfur	Final BW linearly decreased with increasing DDGS, but tended to be greater with FAC than without FAC when feeding 60 percent DDGS; there was a quadratic effect on DMI and feeding 60 percent DDGS decreased DMI	Increasing diet DDGS decreased HCW and LM area, but marbling scores improved when feeding 20 and 40 percent DDGS with FAC compared with the same DDGS inclusion without FAC	Pogge et al., 2016
Steers, 428 kg	Not reported; 4-5 percent (Low) or 7-9 percent (Med) crude fat	Corn or barley diets with Low or Med DDGS	No effect of DDGS oil content on final BW and ADG, and Gain:Feed was greater from barley-based diets	No effect of DDGS oil content or grain type on carcass traits	Rodenhuis et al., 2016
Year 1 – Steers, 396 kg Year 2 – Steers, 436 kg	25 percent; crude fat content not reported	Two-year study using stocker diets containing 75 percent corn silage and 25 percent corn gluten feed, or 25 percent DDGS, or 10 percent soybean meal and 15 percent ground corn, placed on tall fescue pasture for 30 days, and fed the same as the stocker period in during the 100 day finisher period	Steers fed DDGS diet had greater ADG and Gain:Feed than those fed corn-soybean meal	No differences in carcass characteristics due to diet except steers fed corn gluten feed had greater LM area and marbling scores; steaks from steers fed DDGS were more tender based on sensory panel	Stelzleni et al., 2016
Steers, 428 kg	20 percent; crude fat content not reported	0, 0.4, or 0.6 percent urea added to 12 percent high moisture corn, 20 percent DDGS, 10 percent ryegrass haylage and dry-rolled corn diets	0.6 percent urea diet increased carcass adjusted ADG and Gain:Feed, but final BW and DMI were similar among treatments	Carcass characteristics were similar among dietary treatments	Ceconi et al., 2015
Steers and heifers, 351 kg	0 or 60 percent DDGS; 6.9 percent crude fat	Corn-based diet fed for 126 days and 60 percent DDGS diet fed for 70 days followed by a corn-based diet until day 126	Feeding the corn-based diet increased ADG, DMI, and Gain:Feed during the first 70 days but feeding DDGS increased ADG, DMI, and Gain:Feed from 71 to 126 days resulting in no differences in ADG and Gain:Feed for the overall feeding period	-	Nuñez et al., 2015
Steers, 450 kg	0, 20, 30 percent; crude fat content not reported	Barley grain and barley silage diets contained increasing DDGS as a replacement for barley grain	Feeding 20 percent DDGS had no effect of growth performance but feeding 30 percent DDGS decreased Gain:Feed	Feeding 20 percent DDGS had no effect on carcass traits and feeding 30 percent DDGS increased desirable fatty acids in beef	He et al., 2014

Table 5. Summary of 28 published studies evaluating growth performance and carcass characteristic responses[1] of finishing beef cattle fed various types of DDGS diets since 2009

Growth phase, initial BW	DDGS inclusion; crude fat content	Feeding conditions	Growth Responses	Carcass Responses	Reference
Steers, 287 kg	0 percent, 0.5 percent, or 1 percent of BW daily of DDGS; 11.1 percent crude fat	84-day feeding period where steers were fed medium quality grass/legume hay ad libitum and increasing amounts of supplemental DDGS	Quadratic response to ADG and Gain:Feed where the increase in Gain:Feed was less when feeding one percent DDGS	Increasing DDGS increased LM area, backfat thickness, and rump fat thickness	Islas et al., 2014
Steers, 359 kg	32 percent DDGS and 7 percent condensed distillers solubles; crude fat content not reported	84-day feeding period of six diets containing 3.5 to 11.4 percent NDF from bromegrass hay with 0.46 percent dietary sulfur from DDGS and condensed distillers solubles	No effect of NDF level on final BW, ADG, and Gain:Feed, but DMI intake increased linearly.	-	Morine et al., 2014
Steers, 355 kg	60 percent; crude fat content not reported	60 percent DDGS, 20 percent corn silage, 13-14 percent ground corn, 4 percent supplement, and 0 to 2.5 percent CaO	Increased CaO linearly increased ADG and Gain:Feed, but linearly decreased DMI	Carcass yield linearly increased up to 1.6 percent CaO but did not affect other carcass characteristics	Nuñez et al., 2014
Steers, 368 kg	0, 16.7, 33.3, 50 percent wet (WDGS) or DDGS (dry matter basis); crude fat content not reported	Diets contained 10 percent chopped alfalfa/grass haylage and increasing levels of WDGS or DDGS to replace whole corn grain	No effect of WDGS or DDGS or inclusion rate on final BW and ADG; liver abscess score decreased linearly with increasing DDGS level	No effect of diet on carcass yield, HCW, marbling score, lean yield, or lean color	Salim et al., 2014
Steers, 336 kg	50 percent DDGS or modified wet DDGS with solubles (MWDGS); crude fat content not reported	DDGS or MWDGS replaced alfalfa hay and corn husklage, with or without 1.2 percent CaO	Feeding CaO treated DDGS decreased dry matter intake, had no effect on ADG, and improved Gain:Feed compared with those not fed CaO	-	Schroeder et al., 2014
Steers, 345 kg	20 or 40 percent; crude fat content not reported	Diets contained coarse- or fine-rolled corn and 20 or 40 percent DDGS	Corn processing or DDGS had no effect on final BW and ADG, but DMI decreased and Gain:Feed increased with increasing DDGS level	No effect of increasing DDGS inclusion rate on carcass characteristics or quality	Swanson et al., 2014
Steers, 268 kg	1 percent of BW; crude fat content not reported	Winter grazing dormant tall grass pasture for 121 days with supplements of 1 kg/day of a cottonseed meal, 1 percent of BW of corn-soybean meal or soybean hulls and meal, or DDGS	Steers supplemented with corn-soybean meal had greater ADG than those fed soybean hulls and meal or DDGS	Energy supplementation increased mesenteric fat and YG but had no effect on 12th-rib fat thickness or marbling score	Sharman et al., 2013
Steers, 335 kg	0, 25, 40, 70 percent dry matter of modified wet DDGS with solubles (MWDGS); 10.4 percent crude fat	Diets contained 15 percent corn silage and increasing MWDGS to replace shelled corn and soybean meal	No differences in MWDGS inclusion rate on ADG or final BW; feeding 0 percent or 70 percent MWDGS resulted in the lower DMI but Gain:Feed was greatest when feeding 70 percent MWDGS	Steers fed 70 percent MWDGS had smaller ribeye areas and quality grades declined with increasing MWDGS	Veracini et al., 2013

Table 5. Summary of 28 published studies evaluating growth performance and carcass characteristic responses[1] of finishing beef cattle fed various types of DDGS diets since 2009

Growth phase, initial BW	DDGS inclusion; crude fat content	Feeding conditions	Growth Responses	Carcass Responses	Reference
Steers from grazing winter wheat pasture, 363 to 403 kg	35 percent; 12.2 percent crude fat	Two-year study with two groups of steers fed DDGS diets replacing steam flaked corn, urea, and cottonseed meal	No difference in BW gain but feeding dry rolled-corn improved Gain:Feed compared with control and DDGS diets	No difference in LM area, YG, marbling score but feeding steam flaked corn increased dressing percentage, 12th rib fat thickness, and empty body fat	Buttrey et al., 2012
Steer calves, 297 kg	22.5 percent wheat or corn DDGS; crude fat content not reported	Dry-rolled barley (71 percent), 5 percent barley silage, and 2 percent supplement with wheat or corn DDGS	Corn DDGS increased ADG and Gain:Feed compared with wheat DDGS; ADG and DMI was greater for corn DDGS than control diet	Corn DDGS had a fewer carcasses with YG 1 and more with YG grade 2 and 3 compared with steers fed the control diet	Hallewell et al., 2012
Steers, 336 kg	20, 40, or 60 percent; crude fat content not reported	Diets contained 20, 40, or 60 percent DDGS with dry-rolled corn or high moisture corn in 5 percent alfalfa hay and 10 percent corn silage diets	No cases of PEM occurred; carcass-adjusted final BW and ADG decreased quadratically, but Gain:Feed was not affected by feeding increasing DDGS diets; corn processing method did not affect growth performance	Increasing diet DDGS level decreased HCW, fat depth, and YG	Neville et al., 2012
Steers, 252 kg	65 percent; crude fat content not reported	Diets contained 65 percent DDGS or corn limited fed to predicted gain of either 0.9 or 1.4 kg BW/day during growing and finishing phases	Overall ADG, DMI, and Gain:Feed were greater when feeding corn during grower but not during finisher compared with DDGS	During the growing phase, feeding DDGS to achieve greater ADG increased marbling but feeding corn to increase ADG decreased marbling	Felix et al., 2011
Steers, 403 kg	0 or 35 percent wet DDGS with solubles (WDGS); 6.7 or 12.9 percent crude fat	Control diet contained 85 percent dry-rolled and high moisture corn with 10 percent sorghum silage and 35 percent reduced-oil or high-oil WDGS were added to replace corn and urea	Feeding high-oil WDGS increased ADG and final BW compared with feeding reduced-oil WDGS or corn diets; no difference in DMI, ADG, and Gain:Feed of cattle fed reduced-oil WDGS and corn diets	Feeding high-oil WDGS increased HCW compared with feeding corn or reduced-oil WDGS diets, but no effect on other carcass traits	Gigax et al., 2011
Steers, 306 kg	24.5 percent; crude fat content not reported	Stocker diet contained 75 percent corn silage with 25 percent DDGS, corn gluten feed, or soybean meal and fed for 84 days and fed same protein supplements for 100 days of finishing	-	No effect of supplement on carcass yield and quality, but steaks from steers fed DDGS or corn gluten feed were more tender than those fed soybean meal	Segers et al., 2011
Yearling steers, 406 kg	30 percent; 12.0 percent crude fat	Steam-flaked con or dry-rolled corn diets containing 30 percent DDGS with moderate S (0.42 percent S) or high S (0.65 percent S achieved by adding H_2SO_4)	High sulfur diets decreased dry matter intake and ADG but had no effect on Gain:Feed	High sulfur diets decreased HCW and YG but did not affect dressing percentage, liver abcesses, 12th-rib fat thickness, LM area, or quality grades	Uwituze et al., 2011

Table 5. Summary of 28 published studies evaluating growth performance and carcass characteristic responses[1] of finishing beef cattle fed various types of DDGS diets since 2009

Growth phase, initial BW	DDGS inclusion; crude fat content	Feeding conditions	Growth Responses	Carcass Responses	Reference
Steers, 349 kg	20 or 40 percent DDGS or 20 or 40 percent wet DDGS with solubles (WDGS); crude fat content not reported	DDGS or WDGS replaced all of the soybean meal and a portion of cracked corn	-	Feeding WDGS or DDGS increased carcass fat thickness, YG, and resulted in a lower percentage of YG 1 and 2, and α-tocopherol content in ground beef than steers fed the control diet; feeding WDGS and DDGS had no effect on conjugated linoleic acid content of meat, but increased PUFA content making it more susceptible to peroxidation	Koger et al., 2010
Heifers, 353 kg	0 or 25 percent: 10.1 percent crude fat	Diets contained steam-flaked corn and 11 percent corn silage with or without 25 percent DDGS or steam-flaked corn and 6 percent alfalfa hay with or without 25 percent DDGS	Feeding DDGS had no effect on ADG, DMI, or Gain:Feed; liver abscesses were greater when DDGS was not included in the diet	No differences in HCW, carcass yield, fat thickness, quality or YG among diets	Uwituze et al., 2010
Steers, 257 kg	0, 10.5, or 17.5 percent in growing diet; 0, 11.4, or 18.3 percent in finishing diet; crude fat content was not reported	Diets contained increasing amount of DDGS to replace dry-rolled barley for an 84-day grower period and a 112-day finisher feeding period	No difference in initial and final BW, but DMI decreased and ADG and Gain:Feed increased in the growing period by feeding DDGS diets; DDGS decreased DMI during the finishing period but tended to increase Gain:Feed with no difference in DDGS inclusion rate	Feeding DDGS increased marbling score and YG, but tended to decrease rib eye area; feeding the high DDGS diet increased backfat thickness	Eun, J.-S. et al., 2009
Steers, 443 kg	25 or 50 percent; 13.9 percent crude fat content	Corn-based diets containing 25, or 50 percent DDGS, 25 percent DDGS diets containing 12 percent corn gluten feed, or 2.4 or 2.8 percent supplemental soybean oil	Steers fed the 25 percent DDGS diet had greater ADG and Gain:Feed than those fed 50 percent DDGS diets with elevated protein or elevated protein and fat	Steers fed the 25 percent DDGS diet had greater HCW, marbling scores, and quality grades, but there were no differences in carcass yield, 12th-rib fat depth LM area, YG, shear force or meat peroxidation among treatments	Gunn et al., 2009
Steers, 296 kg	30 percent; 9.7 percent crude fat	Growing and finishing diets contained combinations of 0 or 30 percent DDGS	Growing and finishing period showed no differences in DMI, ADG, and Gain:Feed from feeding DDGS	DDGS inclusion rate had no effect on LM area, 12th-rib fat thickness, YG, marbling, and tenderness but steaks from steers fed 30 percent DDGS in the finisher or throughout were juicier and more flavorful	Leupp et al., 2009

[1] Abbreviations used: ADG = average daily gain, BW = body weight, DMI = dry matter intake, Gain:Feed = gain to feed ratio, HCW = hot carcass weight, LM = loin muscle, YG = yield grade

Feeding DDGS to Growing or Stocker Cattle

Less research has been conducted related to feeding corn DDGS to other ages of cattle. However, DDGS is an excellent feed ingredient that can be effectively used to supplement energy and protein in the diet when cattle are fed low-quality forages. When DDGS is added to diets containing forages low in phosphorus, the phosphorus in DDGS will be of significant value. Five studies have been conducted with growing or stocker cattle to evaluate feeding up to 60 percent DDGS diets (Table 6). In general, feeding DDGS diets resulted in either no effects or improved growth performance and carcass traits when DDGS was fed.

Feeding DDGS to Beef Calves

Three studies have been conducted with beef calves to evaluate feeding up to 60 percent DDGS diets (Table 7). In general, feeding DDGS diets resulted in increased growth performance and improvements in various carcass traits when DDGS was fed.

Feeding DDGS to Pastur-Grazing Cattle

An additional three studies have been conducted with pasture grazing to evaluate the benefits of supplementing DDGS on growth and subsequent carcass responses (Table 8). In general, feeding DDGS supplements improved growth performance and carcass traits.

Table 6. Summary of five published studies evaluating growth performance and carcass characteristic responses[1] of growing or stocker beef cattle fed various types of DDGS diets since 2009

Growth phase, initial BW	DDGS inclusion; crude fat content	Feeding conditions	Growth Responses	Carcass Responses	Reference
Growing/stocker cattle					
Year 1 - Steers, 305 kg Year 2 – Steers and heifers, 301 kg	25 percent; 10.9 percent crude fat	Two-year study of two groups fed corn silage-based diets (75 percent dry matter) with 25 percent corn gluten feed, 25 percent DDGS, or 25 percent soybean meal and ground ear corn	Steers fed DDGS and corn-soybean meal diets had greater ADG, DMI was less and Gain:Feed was greatest for those fed DDGS; cost per kg gain was lowest for steers fed DDGS	No difference in predicted carcass traits among dietary treatments using ultrasound	Segers et al., 2013
Steers, 198 to 208 kg	Dry-rolled corn or DDGS supplement fed at 0.5 percent of BW; crude fat content was 11.6 percent	Two-year study of two groups of steers grazing winter wheat pasture with or without supplemental dry-rolled corn or DDGS	ADG increased 8 percent by feeding DDG supplement compared to no supplement or dry-rolled corn	-	Buttrey et al., 2012
Steers and heifers, 238 kg	60 percent; crude fat content not reported	0, 100, or 200 mg Cu/kg dry matter was added to 60 percent DDGS diets with 10 percent long stem grass hay, 15 percent pelleted soy hulls, and 15 percent supplement	No effect of Cu supplementation on ADG but Gain:Feed linearly increased with increased Cu supplementation	No effect of Cu supplementation on HCW, LM area, YG, backfat or marbling score	Felix et al., 2012a
Steers, 277 kg	60 percent; crude fat content not reported	0 or 10 percent haylage, with 0 or 33 mg monensin/kg diet, and 60 percent DDGS, 10 percent corn silage, 15 percent supplement, and 5 or 15 percent corn	ADG increased in 10 percent haylage diets and was further increased by adding monensin, but DMI and Gain:Feed decreased with added haylage	-	Felix and Loerch, 2011
Holstein bulls, 246 kg	0, 0.8, or 1.6 kg/day of DDGS; crude fat content not reported	Corn silage was provided ad libitum with 1.1 kg soybean meal, 1.5 kg rapeseed meal, 1.6 kg DDGS, or 0.8 kg rapeseed meal and 0.8 kg DDGS daily	ADG was lower when feeding DDGS compared with DDGS plus rapeseed meal but not different than other treatments; there were no differences in Gain:Feed among diets	No effect on final BW, carcass yield, and internal fat	Meyer et al., 2010

[1] Abbreviations used: ADG = average daily gain, BW = body weight, DMI = dry matter intake, Gain:Feed = gain to feed ratio, HCW = hot carcass weight, LM = loin muscle, YG = yield grade

Table 7. Summary of three published studies evaluating growth performance and carcass characteristic responses[1] of growing or stocker beef cattle fed various types of DDGS diets since 2009

Growth phase, initial BW	DDGS inclusion; crude fat content	Feeding conditions	Growth Responses	Carcass Responses	Reference
Calves					
Heifers and steers, 156 kg	11 to 34; crude fat content not reported	Four diets providing high fat with high or low crude protein, and low fat with high or low crude protein to replace corn	High protein diets increased ADG, and calves fed the corn diet had decreased DMI but increased Gain:Feed compared with DDGS diets	High fat diets increased carcass 12th rib fat and marbling score, and high protein diets decreased marbling score. No differences in HCW, LM area, or YG	Segers et al., 2014
Holstein steers, 112 kg	0, 10, 20, or 30 percent; crude fat content not reported	Diets contained increasing levels of DDGS to replace steam-flaked corn and fed for 305 days	Increasing DDGS levels linearly increased ADG and Gain:Feed responded quadratically during initial 126 day feeding period but during final 179 day period and overall there were no effects on growth performance	HCW was greatest when feeding 20 percent DDGS but no other effects on carcass characteristics were observed among DDGS inclusion rates	Carrasco et al., 2013
Early weaned steers, 200 kg	0, 30, or 60 percent DDGS; crude fat content was 9.8 percent	20 percent corn silage containing 0, 30, or 60 percent DDGS for 99 days then fed a common diet until slaughter	Dietary DDGS inclusion level had no effect on ADG, DMI, or Gain:Feed during growing phase and had no carryover effects on growth performance during the finishing phase	Dressing percentage, HCW, fat thickness responded quadratically to DDGS inclusion rate, there were no effects on marbling, but the ratio of intramuscular fat to subcutaneous fat increased by feeding 30 to 60 percent DDGS and decreased by feeding 0 to 30 percent DDGS	Schoonmaker et al., 2013

[1] Abbreviations used: ADG = average daily gain, BW = body weight, DMI = dry matter intake, Gain:Feed = gain to feed ratio, HCW = hot carcass weight, LM = loin muscle, YG = yield grade

Table 8. Summary of 3 published studies evaluating growth performance and carcass characteristic responses[1] of grazing beef cattle fed various types of DDGS diets since 2009

Growth phase, initial BW	DDGS inclusion; crude fat content	Feeding conditions	Growth Responses	Carcass Responses	Reference
Grazing cattle					
Steers, 204 kg	0, 0.25, or 0.5 percent of BW; 13.3 percent crude fat	Two-year study of steers grazing desert rangeland with shrubs in northern Mexico and fed increasing amounts of DDGS supplement three times weekly	Final BW, ADG, and supplement conversion increased with increasing DDGS supplementation	-	Murillo et al., 2016
Steers, Year 1 = 206 kg Year 2 = 230 kg	DDGS supplemented at 0, 0.2, 0.4, or 0.6 percent of BW; 12.1 percent crude fat	Two-year study with grazing periods of 56 to 58 days on native range during forage growing season and fed increasing levels of DDGS supplementat 0, 0.2, 0.4, or 0.6 percent of BW	ADG increased linearly with increasing level of DDGS supplement	-	Martinez-Pérez et al., 2013
Yearling steers, 321 kg	1 percent of BW during grazing period; 40 percent during finishing period; crude fat content not reported	Bromegrass pasture with supplement containing low S (0.34 percent S from DDGS) or high S (0.47 percent S from DDGS and $NaSO_4$); finisher diets were 48 percent corn, 40 percent DDGS, 8 percent chopped hay	No effect of dietary S on ADG during the pasture period; Increasing diet S decreased ADG during subsequent finishing period but did not affect DMI and Gain:Feed	Feeding high dietary S during the finishing period decreased HCW but had no effect on carcass fat, LM area, yield grade, or marbling score	Richter et al., 2012

[1] Abbreviations used: ADG = average daily gain, BW = body weight, DMI = dry matter intake, Gain:Feed = gain to feed ratio, HCW = hot carcass weight, LM = loin muscle, YG = yield grade

Beef quality

In general, feeding diets containing typical amounts of DDGS (up to 30 percent of dry matter intake) does not change the quality or yield of beef carcasses, and it has no effect on the sensory and eating characteristics of beef (Erickson et al. 2005). An increasing number of studies have evaluated the quality and sensory characteristics of beef from cattle fed wet or DDGS, and results consistently show no negative effects on eating characteristics of beef from cattle fed high dietary levels of DDGS.

Roeber et al. (2005) evaluated color, tenderness and sensory characteristics of beef strip loins from two experiments where wet or dried corn DDGS were fed to Holstein steers at levels up to 50 percent of the ration. There were no differences in tenderness, flavor and juiciness. Similarly, Jenschke et al. (2006) showed finishing beef cattle fed diets containing up to 50 percent wet distiller's grains (dry matter basis) produced steaks similar in tenderness, amount of connective tissue, juiciness or off-flavor intensity. In fact, steaks from cattle fed the 0 and 10 percent wet DDGS with solubles diets were most likely to have an off-flavor compared to steaks from cattle fed the 30 and 50 percent wet DDGS with solubles diets. Gordon et al. (2002) fed diets containing 0, 15, 30, 45, 60 or 75 percent DDGS to finishing heifers during a 153-day finishing trial and observed there was a small, linear improvement in tenderness of steaks from cattle fed increasing amounts of DDGS.

Koger et al. (2010) fed Angus crossbred steers diets containing 20 or 40 percent wet or dry DDGS with solubles to replace all of the soybean meal and some of the cracked corn. Carcasses of steers fed DDGS had greater fat thickness and improved yield grades than steers fed the dry-rolled corn, soybean meal and alfalfa hay control diet. Loin muscle from steers fed DDGS had higher ultimate pH values than loins from steers fed wet DDGS. Ground beef from steers fed DDGS had higher α-tocopherol compared to those fed the control diet, but steers fed 40 percent DDGS produced ground beef with higher TBARS (thiobarbituric acid reactive substances), which is an indicator of lipid peroxidation, on day two of retail display than ground beef from steers fed 20 percent DDGS diets. These researchers concluded steers fed DDGS may need to be marketed earlier than normal to avoid excess external fat, but there are no adverse or beneficial effects on the incidence of "dark cutters" retail display life of ground beef or meat tenderness.

However, beef from cattle fed distillers grains have increased polyunsaturated fatty acids which may be more susceptible to oxidative rancidity.

Leupp et al. (2009) showed no differences in growth performance when steers were fed 0 or 30 percent DDGS in the growing or finishing period. Marbling and tenderness were not affected by diet, but steaks from steers fed DDGS during finishing were juicier and had more flavor. These data suggest DDGS can be included at 30 percent dietary dry matter in the growing or finishing period to partially replace dry-rolled corn with no detrimental effects on performance, carcass characteristics or sensory attributes. However, feeding 30 percent DDGS may negatively affect steak color.

Similarly, Segers et al. (2011) showed the composition and tenderness of longissimus lumborum steaks were unaffected by feeding diets containing 25 percent DDGS or corn gluten feed compared with using soybean meal as a protein supplement from weaning to harvest. However, similar to the effects of steak color observed by Leupp et al. (2009), trained panelists in this study also observed differences in perceived color, but overall color was similar among steaks among the dietary treatment groups. Unlike the study by Koger et al. (2010), there were no differences in TBARS concentration among treatment groups, but steaks from steers fed DDGS became more discolored after nine days of retail display, and contained greater polyunsaturated fatty acid content, which suggests lipid oxidation may occur and reduce the shelf life for fresh meat products from cattle fed DDGS. Results from this study also indicated DDGS and corn gluten feed can be substituted for soybean meal and a portion of corn in beef cattle diets from weaning to slaughter while maintaining meat quality.

Aldai et al. (2010a,b) compared the effects of feeding wheat versus corn DDGS to feedlot cattle on meat quality and showed wheat DDGS had no negative effects on meat quality. In contrast, feeding corn DDGS had some positive effects on meat quality such as improved tenderness and palatability compared to beef from cattle fed the barley control diet.

Impact of feeding DDGS on E. coli O157:H7 shedding

In 2007, there was a dramatic increase in interest in identifying and understanding the possible reasons for the increases in E. coli O157:H7 in ground beef contamination in the U.S. Because of the exponential increase in ethanol and distiller's grains production during this same time period, there were some suspicions feeding distiller's grains were contributing to this problem. As a result, researchers began conducting studies to determine if there was a relationship between feeding distiller's grains with solubles and the increased incidence of E. coli O157:H7 in beef. However, research results from several studies have shown there is no consistent effect of feeding DDGS on E. coli O157:H7 shedding in beef cattle. The response to E. coli O157:H7 shedding may be affected by DDGS feeding level and other dietary ingredients such as type of corn processing. Currently, there is no scientific evidence suggesting the levels of DDGS being fed is a cause for E. coli O157:H7 contamination in ground beef. Refer to Chapter 18 of this handbook for a more detailed, comprehensive summary of research results related to the potential association of DDGS with the prevalence of fecal shedding of E. coli O157:H7.

Feeding DDGS to Beef Cows

Other potential uses of DDGS include providing it as a creep feed for calves nursing cows, a supplement for grazing cattle and a supplement for low-quality forages and crop residues that might be fed to growing calves, gestating beef cows or developing beef heifers. However, unlike growing-finishing beef cattle, less research has been conducted on feeding DDGS to beef cows. Loy et al. (2005a) published an initial summary of results from including DDGS in beef cow diets, and indicated the best applications for using DDGS are in situations where 1) supplemental protein is needed (especially when feeding low quality forages) to replace corn gluten feed or soybean meal, 2) a low starch, high fiber energy source is needed to replace corn gluten feed or soy hulls and 3) when a source of supplemental fat is needed.

DDGS as a supplemental protein source

Previous research has shown when DDGS was supplemented to provide 0.18 kg of protein/day to beef cows grazing native winter range in Colorado, it compared favorably to alfalfa hay or cull navy beans (Smith et al., 1999). Shike et al. (2004) compared performance effects of feeding corn gluten feed or DDGS as a supplement to ground alfalfa hay to lactating Simmental cows and observed that cows fed DDGS gained more weight, but produced less milk compared to cows fed corn gluten feed. However, there were no differences between cows fed DDGS and those fed corn gluten feed on calf weights and rebreeding performance. In a subsequent study, Loy et al. (2005a) reported that limiting feeding total mixed rations of ground corn stalks supplemented with either DDGS or corn gluten feed to lactating Angus and Simmental cows nursing calves resulted in no differences in milk production and calf weight gains between cows supplemented with DDGS or corn gluten feed.

DDGS as a supplemental energy source

Corn DDGS is an effective energy supplement when fed with low-quality forages. Summer and Trenkle (1998) showed DDGS and corn gluten feed were superior supplements to corn in corn stover diets, but not in high-quality alfalfa diets.

Corn stover (stalks) are low in protein, energy and minerals, but are low in cost and readily available in major corn producing states in the U.S. When low-quality forages (e.g. corn stover) are fed to gestating beef cows in good condition, feeding 1.4 to 2.3 kg of DDGS per day during the last third of gestation will provide adequate protein and energy to meet the cow's requirements (Loy and Miller, 2002). For beef cows fed low quality forage (e.g. corn stalks) in early lactation, supplementing with 2.7 to 3.6 kg of DDGS will meet their protein and energy requirements (Loy and Miller, 2002).

Radunz et al. (2010) evaluated the effects of feeding grass hay, corn or DDGS as late gestation dietary energy sources on pre- and post-partum cow performance. When these energy sources were fed at or above daily requirements, there were no detrimental effects on pre- or post-partum cow performance, and feeding DDGS as a pre-partum dietary energy source reduced daily feed costs during gestation. Dietary energy source affected the partitioning of energy and caused changes in plasma metabolites resulting in heavier birth weights of calves from cows fed DDGS or corn during late gestation compared to those fed grass hay.

DDGS as a supplemental fat source

Supplemental fat may improve reproduction in cow herds experiencing suboptimal pregnancy rates (less than 90 percent). Loy and Miller (2002) indicated that feeding supplements with similar fatty acid profiles to corn oil (found in DDGS) improved pregnancy rates. They also indicated that fat supplementation is most beneficial in feeding situations where protein and/or energy supplementation is necessary.

Engle et al. (2008) evaluated the effects of feeding DDGS compared with soybean hulls, in late gestation heifer diets, on animal and reproductive performance and showed that pre-partum diets containing DDGS, as a source of fat and undegradable intake protein, improved pregnancy rates in well-maintained primiparous beef heifers.

Shike et al. (2009) evaluated the effects of using corn co-products in limit-fed rations on cow performance, lactation, nutrient output and subsequent reproduction. Cows fed DDGS lost 16 kg less body weight and had 0.9 kg/d less milk production, which resulted in calves tending to have lower ADG than for cows fed corn gluten feed. However, in a second experiment, cows were fed 2.3 kg/d of ground cornstalks and isocaloric amounts of corn gluten feed (7.7 kg/d) or DDGS (7.2 kg/d) to meet nutrient requirements. Results from this experiment showed cows fed DDGS tended to lose more weight than those fed corn gluten feed, but there were no differences in milk production or calf ADG. Furthermore, there were no differences in reproductive performance in both experiments, suggesting that DDGS and corn gluten meal can be included up to 75 percent of a limit-fed diet, but the higher fat content of DDGS compared with corn gluten feed did not improve reproduction.

A summary of 13 published studies that have evaluated feeding DDGS supplements to gestating beef cows is shown in Table 9, and 4 additional studies with gestating beef heifers is shown in Table 10. In general, providing DDGS supplements had either no effect or improved reproductive performance of cows or heifers and subsequent growth, carcass or reproduction effects of progeny.

Table 9. Summary of 13 published studies evaluating beef cow reproductive performance and subsequent growth, carcass or reproductive responses[1] of progeny fed various types of DDGS diets since 2009

Reproductive phase	DDGS inclusion rate and crude fat content	Feeding conditions	Reproductive performance responses	Progeny growth, carcass, or reproductive responses	Reference
Gestating cows					
Fall-calving multiparouscows, 623 kg	0, 2.2, or 8.6 kg/day of a 70 percent DDGS and 30 percent soybean hulls supplement; crudefatcontentnot reported	Two-year study where cows grazed endophyte infected tall fescue/red clover pasture and fed increasingamountsoffrom 103daysprepartumtotwo days postpartum	-	No effect on heifer progeny at weaning, breeding,orpregnancy, AI conception rate, pregnancy rate, and calving rate; calf birth weight, percentage of unassisted births, milk production,andcalfBWat 73daysofagefromheifer progenywerenotaffected by supplementation	Shoup et al., 2017

Table 9. Summary of 13 published studies evaluating beef cow reproductive performance and subsequent growth, carcass or reproductive responses[1] of progeny fed various types of DDGS diets since 2009

Reproductive phase	DDGS inclusion rate and crude fat content	Feeding conditions	Reproductive performance responses	Progeny growth, carcass, or reproductive responses	Reference
Multiparous cows	0, 2.5, or 4.7 kg DDGS/day; crude fat content not reported	Fed isocaloric silage TMR with or without supplemental DDGS during early lactation	Increasing DDGS supplement increased milk fat and urea content and feeding 2.5 kg DDGS increased milk lactose content; final BW, ADG, age at puberty, and conception rates were not different among treatments for heifer offspring	-	Taylor et al., 2017
First and second parity cows, 520 kg	0 or 0.35 percent of BW daily, every third day, or every sixth day; crude fat content not reported	Grazing corn residues with or without DDGS supplementation	Daily and every third day supplementation increased ADG, and BCS was greater for daily supplementation	-	Gross et al., 2016
Multiparous cows, 674 kg	0.3 percent of BW last third of gestation and eight weeks after calving; crude fat content not reported	10 week late gestation feeding period of corn stover and silage with or without DDGS supplement	No effects on dystocia but cows fed DDGS had heavier calves at birth due to greater blood glucose, and heavier weaning weights; DDGS supplements increased uterine blood but decreased estradiol and progesterone concentrations	-	Kennedy et al., 2016a,b,c
Multiparous cows, 653 kg	0 or 6.9 kg/day DDGS; crude fat content not reported	Cow-calf pairs were fed diets supplemented with DDGS or soybean meal from calving until 129 days postpartum and consisted of either rye hay and DDGS or corn silage, rye hay and soybean meal	No effects of diet on milk production but milk urea nitrogen and fat increased, wihile milk protein decreased by feeding DDGS; timed AI rates increased by feeding DDGS but no effects on pregnancy rate	ADG and BW of calves increased from cows fed DDGS	Shee et al., 2016
Spring-calving multiparous cows, 657 kg	19 or 39 percent modified wet DDGS with solubles (dry matter basis); crude fat content not reported	Diets contained oatlage, corn silage, and modified wet DDGS with solubles providing protein and the requirement or 129 percent of requirement and fed 78 days pre-partum to calving	No effect of diet on cow BW, BCS, milk production, subsequent reproduction, or progeny pre-weaning growth performance	No effect of progeny finishing growth and carcass marbling scores, but feeding the high protein supplement increased carcass twelth rib fat thickness and YG	Wilson et al., 2016a

Table 9. Summary of 13 published studies evaluating beef cow reproductive performance and subsequent growth, carcass or reproductive responses[1] of progeny fed various types of DDGS diets since 2009

Reproductive phase	DDGS inclusion rate and crude fat content	Feeding conditions	Reproductive performance responses	Progeny growth, carcass, or reproductive responses	Reference
Spring-calving multiparous cows, 688 kg	0 or 7 percent DDGS in post-calving diets, and 45 percent DDGS or modified wet DDGS with solubles used in common progeny feedlot diet	Diets containing 100 or 125 percent of TDN requirements containing ground hay and DDGS or corn bran and ground corn stalks were fed to cows from 83 days prepartum until calving and fed a common g diet postpartum; progeny were fed a common diet containing 45 percent DDGS with solubles until slaughter	Cow BW, BCS, and calf birth weight were greater when fed the high energy diet, but no effects of diet on percentage of unassisted births, calving date, milk production, subsequent pregnancy rate among dietary treatments	No differences in calf weaning weight, initial and final feedlot BW, DMI, ADG, Gain:Feed, or morbidity among dam diet treatments	Wilson et al., 2016b
Cows in a fall-calving system, 632 kg; steers weaned at 186 days of age	Supplement contained 70 percent DDGS, 30 percent soybean hulls; Weaned steers fed 8.1 percent crude fat 25 to 45 percent modified wet DDGS	Grazing endophyte infected tall fescue/red clover pasture with no supplement or low (2.2 kg/cow/day) or high (8.6 kg/cow/day) supplement	Cows fed high amount of supplement had heavier BW pre-calving, post-calving, and post-breeding, but supplementation did not affect calf birth weight, mortality, or assistance with calving. Prepartum supplementation tended to improve AI conception but did not affect pregnancy rate. Early weaning and feeding supplements improved cow BW, BCS, and reproduction.	Weaned steers from cows fed the low supplement diet had greater BW at weaning compared with unsupplemented cows, but minimal performance differences on calf performance based on dam prepartum supplementation level.	Shoup et al., 2015
Spring-calving mature cows, 678 kg	DDGS crude fat content not reported	Limit-fed ground hay (12 kg/day) or a diet containing 60 percent ground corn stalks, 24 percent DDGS, 16 percent corn bran (10.4 kg/day) from 88 days prepartum to calving; postcalving diet contained 22 percent ground hay, 22 percent ground corn stalks, 33 percent DDGS, 24 percent corn bran; progeny fed a common feedlot diet containing wet corn gluten feed, high-moisture corn, corn husklage, and supplement	Cow BW and BCS, and calf birth weight were greater when fed the DDGS diet prepartum, and no difference in unassisted births, pregnancy rate, and milk production	No difference in progeny final BW, ADG, DMI, Gain:Feed, mortality, morbidity, HCW, LM area, backfat, marbling score, and YG during the feedlot feeding period	Wilson et al., 2015a

Table 9. Summary of 13 published studies evaluating beef cow reproductive performance and subsequent growth, carcass or reproductive responses[1] of progeny fed various types of DDGS diets since 2009

Reproductive phase	DDGS inclusion rate and crude fat content	Feeding conditions	Reproductive performance responses	Progeny growth, carcass, or reproductive responses	Reference
Fall-calving mature cows, 603 kg	0 or 2.1 kg DDGS/cow/day until calving; 43 percent DDGS during feedlot period; crude fat content was seven percent	Grazing tall fescue pasture with or without DDGS supplement for 69 days before calving, then moved to another pasture without supplementation; steer progeny fed a common feedlot diet containing 435 DDGS	Cows fed the DDGS supplement had greater BW and BCS, but there were no differences in calving date, milk production, AI conception, or pregnancy rate; no differences in calf birth or weaning weights, or preweaning ADG	No difference in initial and final BW, days on feed, ADG, DMI, Gain:Feed, morbidity, HCW, LM area, marbling score, or YG of progeny steers	Wilson et al., 2015b
Mature cows, 606 kg	4.1 kg/head/day; crude fat content not reported	Diets fed from 167 days of gestation until one week before calving included ad libitum access to grass hay with no supplement, or 5.3 kg/day of shelled corn or 4.1 kg/day of DDGS with 2.1 kg/day hay and 1 kg/day supplement	Cows fed DDGS gained more BW but BCS were not different compared with grass hay only or corn supplement; calf birth weight was increased by feeding DDGS but no effects on dystocia, conception rates, milk production, or milk composition	-	Radunz et al., 2010

Abbreviations used: ADG = average daily gain, AI = artificial insemination, BCS = body condition score, BW = body weight, DMI = dry matter intake, Gain:Feed = gain to feed ratio, HCW = hot carcass weight, LM = loin muscle, YG = yield grade

Table 10. Summary of four published studies evaluating beef heifer reproductive performance and subsequent growth, carcass, or reproductive responses of progeny fed various types of DDGS diets since 2009

Reproductive phase	DDGS inclusion rate and crude fat content	Feeding conditions	Reproductive performance responses	Progeny growth, carcass, or reproductive responses	Reference
Gestating heifers					
Yearling heifers		Dams fed diets fed from 192 days of gestation to 118 days postpartum consisted of corn silage TMR or corn residue with DDGS; heifer progeny provided ad libitum access to DDGS as creep feed until weaning and then fed corn silage, grass haylage, corn stover, soy hulls and soybean meal from weaning to AI	Progeny heifers from dams fed DDGS supplement had greater BW and frame score from weaning to breeding, but ovarian size, follicle count, and age at puberty were not affected by dam diet; BW at puberty and pregnancy rate from AI were greater when dams were supplemented with DDGS and did not affect dystocia rate	-	Gunn et al., 2015
Primiparous heifer, 450 kg	0.83 kg/day; crude fat content not reported	Three-year study during 142 days of gestation and fed grass hay with no supplement or isonitrogenous, isocaloric supplements containing DDGS or corn gluten	Unsupplemented heifers had less DMI and gain less BW. Supplements increased ADG but calf birth weight and subsequent pregnancy rates were similar.	Calf weaning and final BW was not affected by maternal diet and ADG and HCW was similar. Calves from cows fed low amount of supplement had the lowest carcass twelth rib fat and meat tenderness.	Summers et al., 2015a,b
Two-year old heifers, 199 kg	1.2 kg ground raw soybeans and 0.4 kg corn or 1.65 kg DDGS; 11.5 percent crude fat	Ad libitum access to late-harvested Sandhills meadow hay with raw soybean-corn or DDGS supplements from weaning to breeding	Feeding supplemental DDGS increased ADG in year 1 but was not different in year 2; no difference in follicle size, follicle hormones, or pregnancy rate between year 1 and 2; no difference between developmental diets on calf production	-	Martin et al., 2010
Late gestation heifers,	2.8 to 3.1 kg/head/day; 12 percent crude fat	Two-year study with 4 kg/head/day of grass hay with 2.8 to 3.1 kg/head/day of DDGS or 3.2 to 3.5 kg/head/day of soybean hulls for 190 days of gestation to calving	BW increased when feeding DDGS but no effect of supplement on BCS change, calving ease, calf vigor, calf birth weight, weaning weight, or ADG; cows fed DDGS had greater pregnancy rates but did not affect pregnancy distribution or estrus cycles	-	Engle et al., 2008

[1] Abbreviations used: ADG = average daily gain, AI = artificial insemination, BCS = body condition score, BW = body weight, DMI = dry matter intake, Gain:Feed = gain to feed ratio, HCW = hot carcass weight, LM = loin muscle, YG = yield grade

Replacement Heifers

Very little research has been conducted on feeding DDGS to replacement heifers. However, based upon numerous studies for finishing cattle, DDGS would be an excellent source of by-pass protein and energy for developing replacement heifers. In a study by MacDonald and Klopfenstein (2004), replacement heifers grazing brome grass were supplemented with 0, 0.45, 0.90, 1.36 or 1.81 kg of DDGS per day, and results showed that for each 0.45 kg of DDGS supplemented, forage consumption decreased by 0.78 kg per day and ADG increased by 27 g per day.

Loy et al. (2003) evaluated the value of supplementing DDGS daily or three times per week when feeding high-forage diets to growing crossbred heifers. Heifers were provided ad libitum access to grass hay (8.7 percent crude protein) and were supplemented with DDGS or dry-rolled corn. The supplements were fed at two feeding levels and offered either daily or three times per week in equal proportions. Heifers provided daily supplements ate more hay, had greater ADG, but had reduced feed conversion than heifers supplemented three times per week. However, providing low or and high supplementation levels of DDGS resulted in greater ADG and feed conversion than heifers fed the dry-rolled corn (Table 11). Based on these results, the calculated net energy value of DDGS was 27 percent greater than for corn grain.

In a subsequent study, Loy et al. (2004) fed cannulated heifers either no supplement, or DDGS supplemented daily or on alternating days, or dry-rolled corn supplemented daily or on alternating days. As expected, hay intake was greater for heifers that received no supplementation compared to those provided supplements, but there were no differences in feed intake between heifers supplemented with DDGS or corn, but heifers provided supplemental DDGS had higher rates of rumen fiber disappearance than heifers supplemented with corn.

Loy et al. (2008) determined the effect of supplement type, concentration and frequency of feeding on feed intake and growth performance to estimate the energy value of DDGS in a high-forage diet for growing heifers. Results of this study showed supplementing DDGS or dry-rolled corn three times weekly decreased forage intake and body weight gain compared with daily supplementation, but feeding DDGS improved body weight gain and gain:feed compared with feeding supplemental dry-rolled corn. They calculated the TDN of DDGS used in this study was estimated to be 118 to 130 percent the value of corn when fed as a supplement to a grass-hay diet for growing heifers.

Stalker et al. (2004) conducted two experiments to evaluate the effects of supplemental degradable protein requirements when DDGS was fed as an energy source in forage-based diets. Diets were formulated to be deficient (greater than 100 g/day) in degradable protein, but contained excess metabolizable protein. Results of this study showed that adding urea to meet the degradable protein intake requirement is not necessary when DDGS is used as an energy source in forage based diets.

Morris et al. (2005) showed that when individually fed heifers were provided high- or low-quality forage diets with supplementation of either 0, 0.68, 1.36, 2.04 or 2.72 kg DDGS per day, forage intake decreased and average daily gain increased. These results suggest DDGS can be an effective forage supplement to increase growth at times when availability of forage may be limited.

Islas and Soto-Navarro (2011) evaluated the effects of supplementation of DDGS on forage intake and digestion of beef heifers grazing small-grain pasture and showed that supplementation with DDGS up to 0.6 percent of body weight, increased lipid intake as well as lipid and NDF digestibility, with no adverse effects on intake, digestibility and characteristics of ruminal fermentation. Based on these results, DDGS can be successfully used as a supplement to increase lipid intake without negatively affecting forage intake or digestibility in cattle grazing small grains pasture.

Table 11. Growth performance of growing heifers fed native grass hay and supplemented with either corn or DDGS fed at low or high supplementation levels (adapted from Loy et al., 2003).

		Low (0.21 percent of body weight)	High (0.81 percent of body weight)
ADG, kg/d	Corn	0.37	0.71
	DDGS	0.45	0.86
dry matter Intake/ADG	Corn	15.9	9.8
	DDGS	12.8	8.0

Conclusions

Corn DDGS is an excellent energy and protein source for beef cattle in all phases of production. It can be effectively used as an energy source and be fed up to 40 percent of ration dry matter intake for finishing cattle with excellent growth performance and carcass and meat quality. However, at high dietary DDGS inclusion rates, excess protein and phosphorus will be consumed relative to requirements and result in increased excretion of nitrogen and phosphorus in manure. Sulfur content of DDGS should be monitored to adjust diet inclusion rates of DDGS if necessary, to avoid sulfur toxicity, especially when cattle are consuming forages and water with high-sulfur content. Feeding high-DDGS diets to finishing cattle has minimal effects on beef color, may improve sensory characteristics, but increase polyunsaturated fatty acid content which may reduce shelf-life of fresh beef over extended retail case storage periods.

There is no consistent effect of feeding DDGS on E. coli O157:H7 shedding in beef cattle. Dietary level of DDGS and type of corn processing (dry-rolled corn, high-moisture corn, steam-flaked corn) may affect the response to E. coli O157:H7 shedding. Currently, there is no scientific evidence suggesting the level of DDGS fed is a cause for E. coli O157:H7 contamination in ground beef.

Feeding supplemental DDGS to beef cows and heifers supports satisfactory reproductive and lactation performance with minimal effects on growth, carcass or reproductive performance of progeny. The best applications for using DDGS in beef cow diets are in situations where 1) supplemental protein is needed (especially when feeding low quality forages) to replace corn gluten feed or soybean meal, 2) a low-starch, high-fiber energy source is needed to replace corn gluten feed or soy hulls, and 3) when a source of supplemental fat is needed.

For growing heifers, adding urea to meet the degradable protein intake requirement is not necessary when DDGS is used as an energy source in forage based diets. DDGS can be an effective forage supplement to increase growth at times when availability of forage may be limited, and DDGS has 18 to 30 percent higher TDN value than dry-rolled corn for developing heifers.

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CHAPTER 16

Escherichia coli O157:H7 and Listeria monocytogenes Shedding in Beef and Dairy Cattle

Introduction

THE CENTERS FOR DISEASE CONTROL AND PREVENTION (CDC) has identified Escherichia coli O157:H7 and Listeria monocytogenes as two major foodborne pathogens (CDC, 2014). Consumption of ground beef is the most frequently implicated cause of E.coli O157:H7 foodborne illnesses in humans, and food products from cattle have been linked to approximately 75 percent of these outbreaks (USDA-APHIS, 1997; Vugia et al., 2007). Cattle are a major reservoir of E. coli O157:H7 in the mucosal surface of the rectum (Naylor et al., 2003; Gyles, 2007; Hussein, 2007) and in feces (Callaway et al., 2003; Berg et al., 2004; Jacob et al., 2008a,b). In fact studies have shown that up to 30 percent of cattle are carriers of E. coli O157:H7 (Callaway et al., 2006; Reinstein et al., 2007; Stanford et al. 2005).

Many factors affect shedding of these pathogens in ruminants including feed, water, age of animal, and season (Caro et al., 1990; Bach et al., 2002; Renter and Sargeant, 2002; Ho et al., 2007). Manure containing E.coli O157:H7 from cattle housing facilities can contaminate water supplies, be used as irrigation water for crops, or transmitted through other animals (Hill et al., 2006; LeJeune et al., 2001; Sargeant et al., 2003; Thurston-Enriquez et al., 2005). Although diet is considered to be an important factor that may contribute to fecal shedding of these pathogens, the relative impact of grain, grain co-products, and forage is unclear. Initial research by Diez-Gonzalez et al. (1998) showed that an abrupt shift from grain to hay-based rations significantly reduced generic E.coli populations. However, several subsequent research studies that have shown variable results (Hancock et al., 2000; Hovde et al., 1999; Keen et al., 1999).

Listeria monocytogenes are also present in feces of cattle (Pell, 1997; Pauly et al., 1999). Several Listeria spp. (L. innocua, L. monocytogenes, and L. welshimeri) were identified to be present in 9 to 35 percent of fecal samples from healthy beef feedlot cattle (Siragusa et al., 1993). Skovgaard and Morgen (1988) showed that Listeria spp. were present in fecal and silage samples collected from 7 dairy farms, and Ryster et al. (1997) isolated L. monocytogenes from 2 percent of 129 silage samples and 35 of hay silage samples. These results indicate that silage samples may be a potential risk factor for transmission of L. monocytogenes to cattle. However, there is a lack of clear evidence showing a direct relationship between diet composition and pathogen shedding in beef and dairy cattle.

Because of the concerns about potential contamination of meat and milk with E.coli O157:H7 and L. monocytogenes, and the potential role that diet composition may contribute to the risk of contamination, it is important to review the results from research studies involving feeding DDGS to beef and dairy cattle to determine if it is a risk factor.

Does DDGS Increase Shedding of E. coli O157:H7?

Various types of bacteria are present everywhere in the environment and they are present in corn co-products. However, the proportion of grain and forage, and crude protein levels in cattle diets may be a more important factor (Biswas et al., 2016).

An initial report suggested that feeding DDGS increased the shedding of E. coli O157:H7 in cow-calf operations in Scotland (Synge et al., 2003). In a subsequent study, other researchers found that feeding brewer's grains to cattle also increased E. coli O157 shedding, and increased the likelihood of shedding by more than 6-fold (Dewell et al., 2005). In 2007, there was a dramatic increase in interest in identifying and understanding the possible reasons for the increase in E. coli O157:H7 contamination in ground beef in the United States. Because of the exponential increase in distiller's grains production and use in cattle diets during this same time period, there were some suspicions that feeding distiller's grains were contributing to this problem. As a result, researchers began conducting studies to determine if there was a relationship between feeding distiller's grains with solubles and the increased incidence of E. coli O157:H7 in beef. A series of controversial studies conducted by researchers at Kansas State University (Jacob et al., 2008a,b,c), showed low prevalence and inconsistent responses to E. coli O157:H7 shedding in feedlot cattle fed DDGS diets. Despite these inconsistent results, these researchers concluded that feeding distiller's grains increased fecal E. coli O157:H7 shedding in beef feedlot cattle.

However, subsequent studies conducted by researchers at the University of Nebraska (Peterson et al., 2007) showed that feeding up to 50 percent (dry matter basis) wet distiller's grains diets did result in E. coli O157:H7 shedding occurred, but the level of shedding was no different than cattle fed diets containing no DDGS. These results were not in agreement with those reported by Jacob et al. (2008a,b,c).

Furthermore, Nagaraja et al. (2008) collected manure samples from 700 cattle fed either control and DDGS diets for 150 days and showed that the overall prevalence of E. coli O157:H7 shedding was low (5.1 percent) and feeding DDGS had no effect on increasing E. coli O157:H7 shedding. Furthermore, in contrast to earlier studies, Jacob et al. (2009) showed no differences in the fecal shedding of Escherichia coli O157:H7 and Salmonella spp. in cattle fed dry-rolled corn or DDGS.

Callaway et al. (2010) conducted a study to evaluate changes in rumen and fecal bacterial population in beef feedlot cattle fed diets where DDGS replaced 0, 25, or 50 percent of the grain supplement and showed that bacterial populations were different when feeding DDGS, which may have been related to lower rumen pH. Biswas et al. (2016) showed that feeding a high forage and high protein diet resulted in the greatest E. coli O157:H7 shedding in dairy cattle, compared with the low forage and high protein diet which resulted in the least shedding. These results indicate that diet composition and crude protein content can influence E. coli O157:H7 shedding in dairy cattle, but including DDGS in the ration had no effect.

Currently, there is no scientific evidence suggesting that the levels of DDGS being fed is a cause for E. coli O157:H7 contamination in ground beef. Furthermore, if there is a possible connection between feeding of distiller's grains and E. coli shedding, the mechanism has not been elucidated. In vitro studies have not detected any effects of distiller's grains on E. coli O157:H7 populations in mixed ruminal and fecal fluid fermentations (Callaway et al., 2008). It is important to recognize that bacterial contamination (including E. coli O157:H7) in the meat supply can occur during many segments of the food chain, and is not restricted to feed or feed ingredients.

Does DDGS Increase Shedding of L. monocytogenes?

No studies have been conducted to determine the effect of diet composition or feeding DDGS on fecal shedding of Listeria by cattle. Fenlon et al. (1996) showed that about 30 percent of cattle in one herd shed L. monocytogenes after being fed silage. Ho et al. (2007) determined that 38 percent of silage samples evaluated contained L. moncytogenes, and 94 percent of the cows fed silage excreted L. moncytogenes in their feces at least once during the study. Biswas et al. (2016) showed that dairy cows excreted Listeria when fed alfalfa hay that was contaminated with Listeria, which represented the greatest portion of the diet. These researchers showed that feeding a high forage or low protein diet resulted in the greatest Listeria shedding compared with feeding low forage or high protein diets. However, the DDGS source used in this study contained no detectable levels of E. coli or Listeria spp.

Conclusions

Food-borne pathogenic bacteria continue to be a significant threat to human health in many countries around the world, despite the implementation of food safety regulations. Although post-harvest sanitation strategies have reduced E. coli O157:H7 and Listeria monotogenes presence in meat and milk products, implementation of pre-harvest intervention strategies can further reduce the risk of food borne pathogens in food animals before they enter the food chain. Some feedstuffs appear to alter shedding levels of E. coli O157:H7, but these effects have not always been consistent. Fasting and feeding poor quality forages have been shown to increase shedding of E. coli O157:H7 in cattle, but abruptly switching cattle from a high grain diet to a high-quality hay-based diet has been shown to reduce E. coli O157:H7 populations. More research is needed to identify the mechanism (e.g., competitive exclusion, physical removal, forage quality, tannins, lignin, other phenolics) by which feeding forage impacts the microbial populations of the ruminant intestinal tract, including the ecology of E. coli and E. coli O157:H7 populations, in order to implement practical dietary modifications. Furthermore, very little is known about the effects of diet composition and the use of various feed ingredients in Listeria shedding in dairy and beef cattle.

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CHAPTER 17

Reduced-Oil DDGS in Dairy Cattle Diets

Introduction

CORN DDGS IS AN EXCELLENT FEED INGREDIENT for use in lactating dairy cow rations, and about 30 percent of the 38 million metric tons of DDGS co-products produced in the U.S. are consumed by dairy cows. Distiller's grains are an excellent source of energy, readily fermentable fiber, protein and minerals for lactating dairy cows as well as dry cows and replacement heifers. Several excellent literature reviews have been published (Schingoethe et al., 2009; Kalscheur et al., 2012a,b; and Kalscheur, 2013) on the benefits, limitations and feeding applications corn DDGS to dairy cattle. Results from numerous studies have shown that including 20 percent DDGS in total mixed rations (TMR) is optimal for supporting maximum milk production and optimal milk composition (Schingoethe et al., 2009), while minimizing excess phosphorus excretion in manure (Schmit et al., 2009). The major concern with adding more than 20 percent DDGS to TMR is the possibility of causing milk fat depression because the lipid in DDGS is high in polyunsaturated fatty acids. The rumen unsaturated fatty acid load is often considered to be the most-likely risk factor for DDGS to cause milk fat depression, but it is not the only factor associated with milk fat depression (Kalscheur, 2013). Other risk factors that contribute to milk fat depression are variable nutrient composition, lack of adequate effective fiber from various ingredients and increased amounts of fermentable carbohydrates. In fact, Kalscheur (2005) showed feeding diets containing DDGS caused milk fat depression only when diets contained less than 50 percent forage or less than 22 percent NDF from forage. Therefore, when feeding high- (greater than 20 percent) DDGS diets, it is recommended at least 22 percent of total diet NDF be provided by forage. Furthermore, most of the DDGS produced today contains lower crude fat content (5 to 9 percent) compared to traditional high-oil DDGS (greater than 10 percent crude fat), which will result in less capacity for oil in DDGS to modify the rumen microbial environment and reduces the risk of milk fat depression. Therefore, if appropriate diet formulation approaches are used when feeding DDGS, milk fat depression is unlikely to occur.

Nutritional Composition of DDGS for Dairy Cattle

Nutritional advantages of DDGS for dairy cattle

There are several nutritional advantages of corn DDGS compared with other protein ingredients in dairy cow rations (Yildiz and Todorov, 2014).

1. Relatively high protein content (26 to 38 percent)
2. High-energy content (2.03 Mcal/kg NE_L)
3. High concentration of bypass protein (55 percent of crude protein)
4. Low-starch content reduces the potential of high-energy rations to cause rumen acidosis
5. Contains dried yeast cells that provide vitamins, improves palatability, increased fiber digestion and microbial protein synthesis
6. Highly digestible neutral detergent fiber (NDF) that increases energy content and stimulates rumen microorganisms
7. High methionine content provides the opportunity to blend feed ingredients with lower methionine content
8. Relatively high concentration (0.7 to 0.9 percent) of readily available and inexpensive source of phosphorus
9. Contains no anti-nutritional factors
10. Provides milk production performance comparable to feeding soybean meal and rapeseed meal despite its relatively low lysine content, which enables the lysine-to-methionine ratio to be closer to the recommended 3:1 without affecting milk protein content.

With all of these nutritional benefits from using corn DDGS as a feed ingredient in diets for lactating dairy cows, it is no wonder it is a very popular and widely used energy and protein supplement in the U.S. dairy industry.

Energy

Limited studies have been conducted to determine the energy content and nutrient digestibility of reduced-oil DDGS for ruminants. However, using available published information, Schingoethe et al. (2009) summarized published energy values for corn DDGS and reported the average to be 2.25 Mcal NE_L/kg dry matter, which is about 10 percent greater than corn, and greater than 1.97 Mcal NE_L/kg dry matter reported by NRC (2001). This is due to the relatively high (5 to 12 percent) crude fat content and high proportion of readily digestible fiber (38 percent NDF) in corn DDGS. Fiber in DDGS contains low-lignin content which facilitates high digestibility (62 to 71 percent; Birkelo et al., 2004; vander Pol et al., 2009).

Nuez-Ortín and Yu (2011) used the NRC chemical summary and biological approaches to predict energy values of new co-products from bioethanol production for dairy cows, and estimates are shown in Table 1. Using this approach, true digestible protein and non-fiber carbohydrate is less in corn DDGS than wheat DDGS, but corn DDGS has much greater digestible fatty acids and NDF than wheat DDGS. As a result, the NE_L at 3× maintenance was comparable (2.3 Mcal/kg dry matter) reported by Schingoethe et al. (2009).

Recently, Foth et al. (2015) determined the energy value of reduced-oil DDGS (6.2 percent crude fat) in lactating dairy cows to be 3.82 Mcal DE/kg dry matter at 1× maintenance, 3.41 Mcal ME/kg dry matter at 1× maintenance, and 2.03 Mcal NE_L/kg dry matter at 3×maintenance. These estimates are lower than those reported by Schingoethe et al. (2009) for high-oil (less than 10 percent crude fat) DDGS sources, but similar to the NE_L value reported by NRC (2001). In summary, results from these limited studies suggest the NE_L content at 3× maintenance for high-oil DDGS is 2.25 to 2.30 Mcal/kg dry matter, and about 2.0 Mcal/kg dry matter for reduced-oil DDGS.

Oil content and fatty acid composition of DDGS

One of the primary concerns about using corn DDGS in lactating dairy cow diets is the relatively high crude fat content and concentrations of unsaturated fatty acids which may result in reduced milk fat content. Several surveys of dairy nutritionists (Owens, 2009a) and dairy producers (NASS, 2007) indicated the high crude fat content of DDGS was of moderate to high concern and a primary reason why they did not use DDGS in lactating dairy cow rations.

However, in a meta-analysis of 24 experiments, Kalscheur (2005) showed feeding diets containing DDGS caused milk fat depression only when diets contained less than 50 percent forage or less than 22 percent NDF from forage. Furthermore, most of the DDGS produced today contains lower crude fat content (5 to 9 percent) compared to traditional high-oil DDGS (greater than 10 percent crude fat), which will result in less capacity for oil in DDGS to modify the rumen microbial environment and reduces the risk of milk fat depression. Diaz-Royón et al. (2012) summarized the fatty acid composition of corn DDGS sources from several studies and results are shown in Table 2. The most abundant fatty acids in corn oil extracted from DDGS are linoleic (C18:2) and oleic (C18:1), which represent about 74 percent of the total fatty acids in DDGS. However, from this summary, the fatty acid composition can be quite variable among DDGS sources, labs and analytical procedures.

Rumen degradable and digestible undegraded protein of DDGS

Yildiz and Todorov (2014) summarized published studies that determined rumen degradable protein (RDP) and digestibility of undegraded protein in the small intestine (dRUP) of corn DDGS (Table 3). The large variation in rumen degradability and small intestine digestibility of protein in corn DDGS is likely due to differences in drying temperatures used by ethanol plants when producing DDGS. Similar variation has also been shown for amino acid digestibility, especially lysine, of DDGS among sources for swine and poultry. However in general, the rumen degradability of corn DDGS is relatively low, which is an advantage in ruminant diets. Corn DDGS is a good source of dRUP that ranges between 47 to 64 percent of crude protein. Furthermore, intestinal digestibility of most amino acids exceeds 93 percent, which is slightly less than for soybean meal, except for lysine which is about 8 percent digestible in DDGS compared with 97 percent digestibility in soybean meal. However, data provided by

Table 1. Comparison of true digestible nutrient content and energy value of wheat and corn DDGS using an in situ assay (dry matter basis; adapted from Nuez-Ortín and Yu, 2011)

Measurement	Wheat DDGS	Corn DDGS
True digestible crude protein %	33.5	22.7
True digestible non-fiber carbohydrate %	23.6	6.4
True digestible fatty acids %	3.7	15.1
True digestible NDF %	17.3	33.9
Predicted energy content		
$DE_{3\times}$, kcal/kg dry matter (dairy)	3,470	3,791
$ME_{3\times}$, kcal/kg dry matter (dairy)	3,069	3,439
$NE_{L3\times}$, kcal/kg dry matter (dairy)	1,979	2,299
NE_m, kcal/kg dry matter (beef)	2,110	2,340
NE_g, kcal/kg dry matter (beef)	1,439	1,630

Table 2. Summary of studies reporting the fatty acid composition (percent of total fatty acids) in corn DDGS (adapted from Diaz-Royón et al., 2012)

Fatty acid	Tang et al. (2011)	Ranathunga et al. (2010)	Nyoka (2010)	Owens (2009b)	Martinez-Amezcua et al. (2004)	Anderson et al. (2006)	Average
C12:0	0.02	ND	ND	0.01	0.04	0.78	0.21
C14:0	0.07	0.42	3.95	0.38	0.09	2.45	1.23
C16:0	16.7	14.7	16.9	12.5	12.8	15.5	14.9
C16:1	0.16	0.13	2.46	0.11	0.18	ND	0.61
C18:0	2.62	1.99	2.82	1.68	2.03	2.38	2.25
C18:1	23.1	26.9	21.4	38.2	23.2	17.0	25.0
C18:2	53.7	50.7	40.2	40.3	56.3	52.5	49.0
C18:3	0.45	1.60	1.44	1.05	1.48	4.79	1.80
C20:0	1.99	0.39	0.55	0.26	0.39	1.45	0.84
C20:1	0.29	0.22	3.46	0.14	0.27	ND	0.88
C20:2	ND	0.03	0.13	0.03	0.05	ND	0.06

Table 3. Rumen degradable protein and digestibility of rumen undegraded protein in the small intestine of DDGS for dairy cows (adapted from Yildiz and Todorov, 2014)

Rumen degradable protein (RDP) %	Digestible rumen undegradable protein (dRUP) %	Reference
46.0	-	Firkins et al., 1984
63.3	50.5	Carvalho et al., 2005
48.7	88.8	MacDonald et al., 2007
57.0	86.2	Kononoff et al., 2007
22.0 – 36.5	-	Kleinschmit et al., 2007a
47.0 – 64.0	-	Schingoethe et al., 2009
38.0	64.0	Cao et al., 2009
-	92.4	Mjoun et al., 2010c
43.7 – 66.9	91.9 – 92.1	Kelzer et al., 2010
45.0	-	Schingoethe et al., 2009
69.3	-	Oba et al., 2010

Schingoethe et al. (2009) and Mjoun et al., 2010c showed the concentrations of amino acids, especially lysine (3.15 percent of crude protein) and their intestinal digestibility in corn DDGS are greater than those reported in NRC (2001).

Amino acid digestibility

High-producing lactating dairy cows require high daily intake of crude protein and improved supply and balance of amino acids entering the duodenum to meet the high requirements for milk production and milk protein synthesis. It is generally accepted that the concentration of milk protein slightly increases when feeding increased dietary protein levels to lactating dairy cows. No single feed ingredient contains an adequate amount of rumen undegradable protein with an ideal balance of essential amino acids that matches the amino acid profile of milk and the requirements for optimal milk production. As a result, it is difficult to formulate lactating dairy cow rations that meet the daily requirements all of essential amino acids for milk production using commonly available feed ingredients.

Interest in supplementing rumen-protected lysine in lactating dairy cow diets containing DDGS has been significant in recent years because corn protein sources, such as DDGS, have amino acid profiles that do not match the amino acid profile of milk, and are especially low in lysine content. Balancing diets for metabolizable protein is difficult when using current metabolic models because of variability in feed ingredients, genetic differences in milk yield among cows, environment conditions and their interactions, which leads to inaccurate prediction of intestinally absorbed amino acids. However, several studies have been conducted to evaluate the effectiveness of supplementing dairy cow diets containing DDGS with ruminally protected lysine to determine the potential benefits in milk yield and composition.

Boucher et al. (2009) measured intestinal amino acid digestibility of the rumen-undegraded protein fraction of five sources of DDGS to determine if it contains a constant protein fraction undegradable in the rumen and indigestible in the small intestine. Results from this study showed DDGS does not contain a constant protein fraction both undegradable in the rumen and indigestible in the small intestine. Therefore, based on indigestibility values obtained in this experiment, it appears DDGS contains a protein fraction indigestible in the intestine but partially degradable in the rumen, digestible in the intestine after rumen incubation or both.

Swanepoel et al. (2010a) estimated the rumen escape potential of a ruminally protected lysine product and determined its effects on feed intake, digestibility, milk production and milk composition of high producing dairy cows. Feeding diets supplemented with rumen-protected lysine had no effect on dry matter intake, milk yield or milk true protein and lactose yields, but milk fat concentration and yield decreased. Plasma concentrations of most amino acids, except lysine, decreased when rumen-protected lysine was fed. This suggests lysine was the first limiting amino acid in these diets, and supplementing diets with rumen-protected lysine improved absorption and utilization of other amino acids. However, rumen-protected lysine supplementation had no effect on milk protein synthesis and decreased plasma 3-methylhistidine concentrations, which suggests muscle protein synthesis may have been increased or degradation was reduced. Although lysine may have affected muscle protein turnover and energy metabolism resulting in difference in intake, metabolism and absorption of amino acids, as well as milk production, these researchers recommended not supplementing diets with rumen-protected lysine due to potential negative outcomes resulting in poor predictability of estimating intestinally absorbed lysine requirements.

In a subsequent study, Swanepoel et al. (2010b) compared the use of three metabolic prediction models to estimate the amino acid profiles of intestinally delivered protein in dairy rations and determine if there was enough consistency in nutrient profiles to develop and supplement a common ruminally-protected amino acid premix. Although these researchers reported there appears to be enough consistency in nutrient profiles among commonly used rations to support the use of a ruminally-protected amino acid complex to balance dairy rations, they indicated it was impossible to determine which model predictions were correct.

Robinson et al. (2011) also estimated the rumen escape of ruminally protected lysine in lysine-deficient diets, and its effects on dry matter intake, milk production and plasma amino acid profiles of high producing dairy cows. Feeding rumen-protected lysine increased plasma lysine concentrations in mid-lactation cows, which suggested lysine requirements were exceeded, and supplemental rumen-protected lysine was not needed. Based on previous research from this group, they suggested that body protein turnover is the first priority for amino acid utilization followed by milk component systhesis.

Li et al. (2012) conducted a study to determine in situ ruminal degradability of crude protein, amino acid profiles of ruminal undegradable protein (RUP) and in vitro intestinal digestibility of amino acids for wheat and corn grain and wheat and corn DDGS sources. Ruminal degradation of crude protein was less in DDGS than in corresponding grains, but there was no difference between wheat and corn DDGS. Ruminal degradation of essential amino acids was greater for wheat DDGS compared with corn DDGS, and amino acid profiles of RUP were different among grain types and DDGS sources. Total and essential amino acid intestinal digestibility was highly variable among individual amino acids and feed ingredients, but were not different between wheat and corn DDGS. These results suggest that amino acid availability varies substantially among grain and DDGS sources.

Paz et al. (2013) fed 0, 10 or 20 percent DDGS diets with or without rumen protected lysine (60g/day) to determine effects on milk yield, milk composition and plasma concentrations of amino acids. Cows fed 10 or 20 percent DDGS diets had similar dry matter intake and milk yield compared with cows fed the control diet. Cows fed the 20 percent DDGS diets had greater milk protein concentration and yield, but other milk components were similar, compared with those fed the 0 and 10 percent DDGS diets. Supplementation of rumen-protected lysine in DDGS diets had no effect on milk production or composition. Plasma concentrations of arginine, histidine and valine were lower, and concentrations of leucine and methionine were greater in cows fed the DDGS diets compared with those fed the 0 percent DDGS diet. Although the plasma concentration of lysine decreased as dietary inclusion rate of DDGS increased, supplementation of diets with rumen-protected lysine did not decrease plasma concentrations of other essential amino acids, indicating lysine was not limiting in these diets.

In a subsequent study, Paz and Kononoff (2014) evaluated the effects of feeding isonitrogenous and isocaloric diets containing 15 or 30 percent reduced-oil DDGS with or without rumen-protected lysine supplementation on lactation responses and amino acid utilization. Diet inclusion rate of reduced-oil DDGS had no effect on dry matter intake, milk yield or milk fat and lactose concentrations, but milk protein content decreased when cows were fed diets containing 30 percent reduced-oil DDGS. However, cows fed the 305 reduced-oil DDGS diets had greater amino acid extraction efficiency, and tended to have greater milk protein concentration when the diet was supplemented with rumen-protected lysine, than cows fed the 15 percent DDGS diets. This observation suggests lysine was inadequate in the 30 percent DDGS diets, but there was no difference in milk protein yield among dietary treatments. These researchers speculated the rumen-protected lysine product used, provided less metabolizable lysine than expected, and indicated that lysine, arginine and phenylalanine were the three most limiting amino acids in these diets. These results suggest supplementing lactating dairy cow diets with rumen-protected amino acid may be useful in supplying deficient amino acids, but accurate information about the bioavailability of these amino acids is needed.

Mjoun et al. (2010a) determined the ruminal degradability and intestinal digestibility of protein and amino acids in solvent-extracted soybean meal, expeller soybean meal, extruded soybeans, high-oil DDGS, reduced-oil DDGS, high-protein distillers dried grains and modified wet DDGS with solubles using in situ and in vitro procedures. Intestinal digestibility of most amino acids in the corn DDGS co-products exceeded 92 percent and was slightly less than for the soybean products, except for lysine, which averaged 84.6 percent in distillers co-products compared with 97.3 percent in the soybean products. Results from this study suggest that amino acid availability is comparable between corn DDGS co-products and soybean products for lactating dairy cows.

Mjoun et al. (2010b) evaluated milk production responses and amino acid utilization when feeding diets containing 0 percent DDGS, 22 percent high-oil (percent crude fat), or 20 percent reduced-oil DDGS to dairy cows in early lactation. Diets were formulated to contain similar crude protein, lipid, NDF and NE content. Body weight, body weight change and body condition scores were similar among dietary treatments, but cows fed the control diet tended to increase body condition compared to those fed the DDGS diets (Table 4). There were no differences in dry matter intake, protein intake and net energy. All cows had a positive energy balance from 35 to 120 days in lactation, but cows fed the control diet had greater energy balance, tended to have greater total body energy reserves and less energy efficiency than cows fed the DDGS diets. These results suggest that cows fed the control diet may have preferentially partitioned metabolizable energy toward body energy reserves rather than using this energy for milk production and milk component synthesis. There were no differences in milk yield, or milk fat and lactose content among dietary treatments, but cows fed the DDGS diets had greater milk protein content and yield. Furthermore, feed efficiency tended to be greater and nitrogen efficiency was greater for cows fed the DDGS diets. Amino acid utilization was determined at the peak of milk production (nine weeks of lactation), and showed the extraction efficiency of lysine by the mammary gland was greater when cows were fed the DDGS diets (76 percent) compared to those fed the control diet (65 percent), but mammary uptake of lysine was similar (2.56 g/kg milk) among dietary treatments. Furthermore, mammary uptake of methionine tended to increase in cows fed the DDGS diets. Despite the apparent lysine deficiency, milk protein concentration was increased in cows fed the DDGS diets. These results strongly indicate high-oil and reduced-oil DDGS are good sources of energy and metabolizable amino acids when added at 20 percent of the diet, and lysine content and availability does not limit milk production or milk protein synthesis in lactating dairy cows producing 40 kg of milk per day.

Mjoun et al. (2010c) also evaluated the effects of feeding diets containing 0, 10, 20 or 30 percent low-oil (3.5 percent crude fat) DDGS (to replace soybean meal) to dairy cows in mid-lactation on milk production and composition, as well as amino acid utilization. Increasing dietary DDGS content had no effect on dry matter intake and milk yield, and linearly increased milk fat content while tending to increased milk fat yield. Milk protein yield was not affected by increasing dietary DDGS inclusion level, but milk protein concentration increased quadratically. The efficiency of milk production increased but nitrogen utilization efficiency was not affected by increasing dietary DDGS content. The extraction of lysine from the mammary gland increased linearly, and extraction of methionine decreased linearly. Results from this study showed feeding diets containing up to 30 percent low-oil DDGS provide similar lactation performance and nutritional efficiency compared to cows fed the control soybean protein-based diet.

Pereira et al. (2015) determined the effects of feeding DDGS diets supplemented with rumen-protected lysine and methionine to replace soybean meal on lactation performance of late-lactation cows. Results showed supplementing DDGS diets with rumen-protected lysine and methionine was effective in maintaining milk yield and milk composition when replacing soybean meal in low protein corn silage and rye grass silage diets for late lactation dairy cows producing 21 to 27 kg milk/day.

Table 4. Lactation performance, energy and amino acid utilization and milk composition of feeding high-oil or reduced-oil DDGS to early lactation dairy cows (adapted from Mjoun et al., 2010a)

Measure	Control	22% High-oil DDGS	20% Reduced-oil DDGS
Cow body weight and condition			
Initial body weight, kg	693	682	660
Final body weight, kg	734	722	704
Body weight change, kg/day	0.47	0.47	0.53
Body condition score[1]	3.43	3.32	3.34
Body condition score change/day	0.14	0.02	0.00
dry matter, protein, and energy intake			
Dry matter intake, kg/day	24.8	24.7	24.6
Protein intake, kg/day	4.3	4.3	4.3
NE_I, Mcal/day[2]	41.3	40.1	40.3
NE_M, Mcal/day[3]	11.0	11.0	11.0
NE_L, Mcal/day[4]	26.4	26.5	27.4
Energy balance, Mcal/day[5]	4.39	1.98	1.98
Total energy reserves[6]	20.7	20.0	20.1
Energy efficiency[7]	63.1	66.9	68.1
Milk production and efficiency			
Milk yield, kg/day	39.2	38.9	39.8
Energy-corrected milk yield[8]	38.0	37.8	39.5
Fat-corrected milk yield[9]	35.7	35.3	37.1
Feed efficiency[10]	1.50	1.57	1.61
Nitrogen efficiency[11]	24.5	26.9	26.5
Mammary uptake of essential amino acids, g/kg milk[12]			
Histidine	0.80	0.91	0.98
Isoleucine	2.07	2.40	2.45
Leucine	3.09	4.03	4.38
Lysine	2.52	2.49	2.68
Methionine	0.58	0.83	0.81
Phenylalanine	1.14	1.39	1.58
Threonine	1.18	1.19	1.30
Tryptophan	0.14	0.64	0.50
Valine	2.35	2.87	2.87

Table 4. Lactation performance, energy and amino acid utilization and milk composition of feeding high-oil or reduced-oil DDGS to early lactation dairy cows (adapted from Mjoun et al., 2010a)

Measure	Control	22% High-oil DDGS	20% Reduced-oil DDGS
Milk composition			
Fat %	3.63	3.24	3.57
Fat, kg/day	1.33	1.34	1.40
Protein %	2.82	2.88	2.89
Protein, kg/day	1.07	1.15	1.14
Lactose %	4.90	4.99	4.96
Lactose, kg/day	1.94	1.94	1.96
Total solids %	12.3	12.0	12.4
Total solids, kg/day	4.73	4.70	4.90
Milk urea nitrogen, mg/dL	11.8	10.9	10.1
Somatic cell score[13]	3.38	3.91	3.83

[1] Body condition score: 1 = emaciated to 5 = obese

[2] NE_I = Net energy intake (NE_L, Mcal/kg × dry matter intake, kg/day)

[3] NE_M = net energy for maintenance = Body weight$^{0.75}$ × 0.08; NRC (2001)

[4] NE_L – net energy required for lactation = [milk yield, kg × (0.029 x milk fat %) + (0.0563 × milk protein %) + (0.0395 × lactose %); NRC (2001)

[5] Energy balance = $NE_I - (NE_M + NE_L)$

[6] Total energy reserves = (proportion empty body fat × 9.4) + (proportion empty body protein × 5.55); NRC (2001)

[7] Energy efficiency = $NE_L/NE_I \times 100$

[8] Energy-corrected milk = [0.327 × milk yield, kg] + [12.95 × fat yield, kg] + [7.2 × protein yield, kg]

[9] Fat-correct milk = [0.4 × milk yield, kg] + [15 × fat yield, kg]

[10] Feed efficiency = (energy-corrected milk/dry matter intake) × 100

[11] Nitrogen efficiency = (milk nitrogen, kg/day)/(nitrogen intake, kg/day) × 100

[12] Mamary uptake = arterio-venous difference × mammary plasma flow

[13] Somatic cell score = log somatic cell count

Phosphorus

Phosphorus is one of the most important and costly minerals in animal nutrition, but it is also considered one of the primary contributors to pollution in intensive animal production systems because when it is fed in excess, high concentrations of phosphorus are excreted in manure (Humer and Zebeli, 2015). Schmit et al. (2009) showed including moderate levels (10 percent) in lactating dairy cow rations did not significantly increase phosphorus excretion, but when DDGS is added to dry cow and heifer rations, the amount of plant-available phosphorus increased and exceeded crop nutrient requirements for phosphorus when manure from these cattle was applied.

Phosphorus content in DDGS is high (0.65 to 0.95 percent), and has been shown to be highly available in ruminant diets (Mjoun et al., 2008), and because high-producing dairy cows need supplemental phosphorus in their rations, the addition of DDGS can be used to partially replace expensive inorganic phosphorus supplements. Therefore, to minimize excess phosphorus excretion in manure, dairy cow rations should be formulated to be close to the cow's daily phosphorus requirement (NRC, 2001).

Summary of Initial Studies on Feeding High-Oil DDGS on Lactation Performance and Milk Composition

Schingoethe et al. (2009) summarized numerous studies involving the feeding value of high-oil DDGS for dairy cattle. Corn DDGS is a good source of crude protein (greater than 30 percent CP on a dry matter basis) which is high in ruminally undegradable protein (about 55 percent of crude protein). Corn DDGS is also an excellent source of energy (net energy for lactation is approximately 2.25 Mcal/kg of dry matter), which is derived from the intermediate oil concentration (5 to 12 percent on a dry matter basis) and readily digestible fiber (about 39 percent neutral detergent fiber). Lactation performance is usually similar when cows are fed wet or DDGS, but some research results show a slight advantage for feeding wet DDGS with solubles. Corn DDGS can be used as a partial replacement for both concentrates and forages, but it generally used as a concentrate replacement. This is because adequate effective fiber is needed to avoid milk fat depression when DDGS is used to replace forages in lactating cow diets. Lactating dairy cow diets can contain 20 to 30 percent DDGS on a dry matter basis provided that diets are nutritionally balanced. In fact, several studies have shown feeding DDGS diets containing up to 30 percent DDGS provide similar or increased milk production compared with when cows are fed diets containing common feed ingredients. Although DDGS can be added to lactating dairy cow diets at levels greater than 30 percent (dry matter basis), gut fill may limit dry matter intake and milk production. The fiber in DDGS, is usually considered a replacement for high-starch feed ingredients such as corn, and as a result, minimizes the risk of acidosis but does not necessarily eliminate it.

Kalscheur (2005) conducted a meta-analysis of data from 23 previous experiments and 96 treatment comparisons involving feeding wet (WDG) or dried corn distiller's grains with solubles (DDGS) to lactating dairy cows. These studies were published between 1982 and 2005 and evaluated feeding high-oil DDGS. A summary of several recent studies involving feeding reduced-oil DDGS will be discussed later in this chapter. To evaluate the effects of dietary inclusion rate of wet and dried corn distiller's grains on lactation performance, treatments were divided into five categories of feeding levels: 0 percent, 4 to 10 percent, 10 to 20 percent, 20 to 30 percent and greater than 30 percent on a dry matter basis. The form of the distiller's grains (wet or dried) was also used to separate responses in the analysis.

Dry matter intake (DMI) was affected by both dietary inclusion level and form of the distiller's grains fed (Table 5). For lactating cows fed DDGS, dry matter intake increased as the dietary DDGS inclusion level increased, and was greatest for cows fed diets containing between 20 and 30 percent DDGS. In fact, these cows consumed 0.7 kg more feed per day (dry matter basis) than cows fed the control diets containing no DDGS. Cows fed greater than 30 percent DDGS consumed about the same amount of feed as cows fed control diets. While DMI was increased for cows fed diets containing up to the 20 to 30 percent DDGS, DMI of cows fed WDG diets was greatest at lower inclusion levels (4 to 10 percent and the 10 to 20 percent levels). When WDG was included at concentrations greater than 20 percent, DMI decreased, and cows fed greater than 30 percent WDG had 2.3 kg/day less DMI than the control group, and 5.1 kg/d less than those fed the 4 to 10 percent dietary WDG levels. These results show corn DDGS is highly palatable because DMI is stimulated when DDGS is included up to 20 percent of the dry matter in dairy cow diets. Decreases in feed intake at higher inclusion levels may be caused by high dietary fat concentrations, or in the case of WDGS, high dietary moisture content.

Milk production was not affected by wet or dry form of distiller's grains fed, but there was a curvilinear response to increasing distiller's grains in dairy cow diets (Table 5). Cows fed diets containing 4 to 30 percent distiller's grains produced the same amount of milk (about 0.4 kg/d more milk), than cows fed diets containing no distiller's grains. When cows were fed the highest dietary inclusion rate (greater than 30 percent) of distiller's grains, milk yield tended to decrease, and produced about 0.8 kg/day less milk than cows fed diets containing no distiller's grains. However, cows fed more than 20 percent WDG had decreased milk production, which was most likely related to reduced DMI.

Milk fat percentage varied when feeding wet or dried distiller's grains, but was not affected by dietary level or moisture content (Table 6). Milk fat composition responses observed in this extensive data summary do not support the

Table 5. dry matter intake and milk yield of dairy cows fed increasing dietary levels of wet or dried corn distiller's grains (Kalscheur, 2005)

Diet inclusion level	Dry matter intake, kg/d			Milk yield, kg/d		
(Dry matter basis)	Dried	Wet	All	Dried	Wet	All
0%	23.5^{c}	20.9^{b}	22.2^{b}	33.2	31.4	33.0
4 – 10%	23.6^{bc}	23.7^{a}	23.7^{a}	33.5	34.0	33.4
10 – 20%	23.9^{ab}	22.9^{ab}	23.4^{ab}	33.3	34.1	33.2
20 – 30%	24.2^{a}	21.3^{ab}	22.8^{ab}	33.6	31.6	33.5
> 30%	23.3^{bc}	18.6^{c}	20.9^{c}	32.2	31.6	32.2
SEM	0.8	1.3	0.8	1.5	2.6	1.4

^{a,b,c}Values within a column followed by a different superscript letter differ (P less than 0.05).
No superscript within a column indicates that there was no significant difference between distiller's grains dietary inclusion level.

concerns that feeding high dietary inclusion rates of distiller's grains results in milk fat depression. Many factors can affect milk fat depression, and can be avoided by providing sufficient fiber from forages to maintain adequate rumen function. Distiller's grains are comprised of 28 to 44 percent neutral detergent fiber, but this fiber is finely processed and rapidly digested in the rumen. As a result, fiber from distiller's grains is not considered ruminally effective fiber and should not be considered equal to forage fiber. In addition, high levels of dietary lipid provided from distiller's grain may affect rumen function leading to milk fat depression, but in genral, it is a combination of several dietary factors that can lead to significant reduction in milk fat percentage.

Milk protein percentage was not different among cows fed diets containing 0 to 30 percent distiller's grains, and the form of the distiller's grains did not alter milk protein composition (Table 6). However, milk protein percentage decreased 0.13 percentage units when distiller's grains was included at concentrations greater than 30 percent of the diet compared to cows fed control diets. At the higher dietary inclusion levels, distiller's grains most likely replaced all other sources of protein in the diet. At these high levels of dietary inclusion, lower intestinal protein digestibility, lower lysine concentrations and an unbalanced amino acid profile may have contributed to a reduced milk protein concentration. However, it should be noted the lower milk protein concentrations were more commonly reported in studies conducted in the 1980s and 1990s when the nutrient composition and digestibility of DDGS was different than that produced currently. Results for recent studies have not shown this effect. Lysine is very heat sensitive, and can be negatively affected in DDGS by high temperatures used during the production and drying in some ethanol plants. However, production and drying technology has improved dramatically in ethanol plants since the time these studies were conducted, resulting in improved lysine and amino acid digestibility of DDGS.

Recent Studies Evaluating the Effects of Feeding High-Oil and Reduced-Oil DDGS on Lactation Performance, Milk Composition, Rumen Fermentation and Nutrient Digestibility

Several recent studies have shown numerous benefits of feeding diets containing up to 30 percent high-oil and reduced-oil DDGS diets to lactating dairy cows on milk yield and composition, as well as reductions in methane emissions and the underlying rumen fermentation and nutrient digestibility responses that support these responses. Understanding the effects of feeding corn DDGS to lactating dairy cows on rumen fermentation and nutrient digestibility is important for several reasons including impacts on methane emissions, manure composition and nutrient excretion, as well as potential risk of depressing milk fat content.

Benchaar et al. (2013) evaluated the effects of replacing corn and soybean meal with 0, 10, 20 or 30 percent high-oil DDGS in lactating dairy cow diets on enteric methane emissions, ruminal fermentation characteristics, apparent total tract digestibility, nitrogen balance and milk production of dairy cows. Increasing dietary DDGS levels increased dry matter intake and milk yield, but decreased apparent-total tract digestibility of dry matter and gross energy (Table 7). The acetate to propionate ratio in the rumen decreased linearly as a result of decreased acetate concentration, and methane production decreased linearly with increasing dietary DDGS levels. The reduction in methane production was attributed to increased amounts of lipid provided by DDGS and its effects on rumen fiber degradation, acetate:propionate and protozoa numbers. Nitrogen utilization efficiency was also improved by feeding increasing levels of DDGS, but nitrogen excretion in manure also increased. Results from this study indicate that feeding DDGS to lactating dairy cows is effective in reducing methane emissions while also improving dry matter intake and milk yield.

Table 6. Milk fat and protein concentrations from dairy cows fed increasing levels of wet or dried corn DDGS (Kalscheur, 2005)

Distillers grains inclusion level (dry matter basis)	Milk fat %	Milk protein %
0%	3.39	2.95^a
4 – 10%	3.43	2.96^a
10.1 – 2%	3.41	2.94^a
20.1 – 30%	3.33	2.97^a
> 30%	3.47	2.82^b
SEM	0.08	0.07

a,b Values within a column followed by a different superscript letter differ (P less than 0.05).

No superscript within a column indicates that there was no significant difference between distiller's grains dietary inclusion level.

Table 7. Effects of feeding increasing levels of reduced-oil DDGS to lactating dairy cows on lactation performance, rumen pH, rumen volatile fatty acid and ammonia production, apparent total tract digestibility of nutrients and fecal output (adapted from Benchaar et al., 2013)

Measure	0% DDGS	10% DDGS	20% DDGS	30% DDGS
Initial body weight, kg	700	701	697	698
Final body weight, kg	710	714	724	730
Weight gain, kg/day	0.29	0.35	0.76	0.95
Dry matter intake, kg/day	24.2	24.6	24.4	25.3
Milk yield, efficiency, and composition				
Milk yield, kg/day	32.6	35.1	35.8	36.6
Energy-corrected milk yield, kg/day[1]	35.3	37.8	37.3	37.1
4% fat-corrected milk, kg/day[2]	32.1	34.5	34.1	33.7
Milk/dry matter intake	1.40	1.44	1.44	1.45
Energy-corrected milk/dry matter intake	1.51	1.55	1.50	1.46
Fat-corrected milk/dry matter intake	1.37	1.42	1.37	1.33
Milk fat %	3.93	3.91	3.69	3.47
Milk fat yield, kg/day	1.27	1.36	1.32	1.27
Milk protein %	3.49	3.41	3.31	3.31
Milk protein yield, kg/day	1.13	1.19	1.18	1.20
Milk lactose %	4.60	4.63	4.59	4.58
Milk lactose yield, kg/day	1.50	1.62	1.65	1.68
Milk urea nitrogen, mg/dL	11.1	10.0	9.9	10.6
Somatic cell count ($\times 10^3$/mL)	75	82	133	89
Rumen pH				
Minimum	5.92	5.92	5.98	5.97
Maximum	6.56	6.59	6.64	6.55
Average	6.21	6.21	6.27	6.22
Protozoa ($\times 10^5$/mL)	5.12	5.28	5.42	4.48
Volatile fatty acids				
Total, mM	99.3	96.1	93.6	91.1
Acetate, mol/100 mol	63.4	62.7	61.8	60.1
Propionate, mol/100 mol	21.8	22.1	22.3	23.1
Isobutyrate, mol/100 mol	0.8	0.8	0.7	0.7
Butyrate, mol/100 mol	11.5	12.0	12.8	13.7
Isovalerate, mol/100 mol	1.4	1.2	1.2	1.1
Valerate, mol/100 mol	1.2	1.2	1.2	1.3
Acetate:Propionate	63.4	62.7	61.8	60.1
Ammonia, mg/dL	8.4	7.5	6.7	6.1

Table 7. Effects of feeding increasing levels of reduced-oil DDGS to lactating dairy cows on lactation performance, rumen pH, rumen volatile fatty acid and ammonia production, apparent total tract digestibility of nutrients and fecal output (adapted from Benchaar et al., 2013)

	0% DDGS	10% DDGS	20% DDGS	30% DDGS
Methane production				
g/day	495	490	477	475
g/kg dry matter intake	0.6	20.1	19.7	18.9
% of gross energy intake	6.09	5.80	5.61	5.23
% of digestible energy intake	8.75	8.39	8.17	7.74
g/kg milk	15.6	14.2	13.6	13.2
g/kg fat-corrected milk	15.7	14.3	14.3	14.4
g/kg energy-corrected milk	14.3	13.1	13.0	13.0
g/kg milk fat	396	363	372	390
g/kg milk protein	446	415	411	400
Nutrient intake. apparent total tract digestibility of nutrients, and nitrogen balance				
Dry matter intake, kg/day	23.4	24.4	24.8	25.2
Dry matter digestibility %	70.7	70.2	69.6	68.1
Organic matter intake, kg/day	21.7	22.7	22.9	23.3
Organic matter digestibility %	72.5	71.9	71.1	69.8
Gross energy intake, Mcal/day	104	111	115	119
Gross energy digestibility %	69.6	69.2	68.7	67.6
Neutral detergent fiber intake, kg/day	7.5	8.2	9.0	9.5
Neutral detergent fiber digestibility %	56.0	56.9	57.4	54.8
Acid detergent fiber intake, kg/day	5.1	5.3	5.7	5.9
Acid detergent fiber digestibility %	60.6	60.4	60.3	60.6
Crude protein intake, kg/day	3.8	4.0	4.1	4.3
Crude protein digestibility %	67.3	68.3	68.4	69.2
Starch intake, kg/day	4.3	3.9	3.4	2.8
Starch digestibility %	94.7	95.4	96.2	98.8
Ether extract intake, kg/day	0.9	1.2	1.5	1.8
Ether extract digestibility %	53.0	53.8	57.4	59.4
Nitrogen intake, g/day	606	642	655	682
Fecal nitrogen excreted, g/day	198	204	207	211
Fecal nitrogen excreted as percent of N intake	32.7	31.7	31.6	30.8
Urinary nitrogen excreted, g/day	204	209	213	223
Urinary nitrogen excreted as percent of N intake	33.7	32.7	32.7	32.6
Total nitrogen excreted, g/day	402	413	419	434

Table 7. Effects of feeding increasing levels of reduced-oil DDGS to lactating dairy cows on lactation performance, rumen pH, rumen volatile fatty acid and ammonia production, apparent total tract digestibility of nutrients and fecal output (adapted from Benchaar et al., 2013)

	0% DDGS	10% DDGS	20% DDGS	30% DDGS
Total nitrogen excreted as percent of N intake	66.4	64.4	64.3	63.5
Milk nitrogen, g/day	177	187	185	189
Milk nitrogen as percent of N intake	29.4	29.1	28.2	27.7
Retained nitrogen, g/day	33	42	51	60
Retained nitrogen as percent of N intake	5.3	6.5	7.6	8.9
Productive nitrogen, g/day	204	229	236	248
Productive nitrogen as percent of N intake	34.6	35.6	35.7	36.5

[1] Energy-corrected milk = 0.327 × milk yield (kg/day) + 12.95 × milk fat yield (kg/day) + 7.2 × protein yield (kg/day)

[2] 4 percent fat-corrected milk = 0.4 × milk yield (kg/day) + 15 × milk fat yield (kg/day)

Castillo-Lopez (2014) determined the effects of feeding increasing levels (0 to 30 percent) of reduced-oil DDGS (0 to 30 percent) to lactating cows on lactation performance, rumen fermentation, intestinal flow of microbial nitrogen and total-tract nutrient digestibility. Increasing diet inclusion rates of reduced-oil DDGS had no effect on milk yield and milk fat content, but tended to increase milk protein content (Table 8). Rumen pH was reduced by feeding increasing levels of reduced-oil DDGS, which may be partially attributed to lower TMR particle size and likely resulted in less time cows spent chewing to produce saliva and consequently had less buffering effect on rumen pH. Total ruminal volatile fatty acids and ammonia concentrations, as well as microbial nitrogen flow were not affected by DDGS feeding level. dry matter, organic matter, neutral detergent fiber and non-fiber carbohydrate digestibility tended to increase when feeding increasing amounts of reduced-oil DDGS. Results from this study indicate feeding up to 30 percent reduced-oil DDGS provides excellent lactation performance and milk composition without affecting rumen volatile fatty acid concentrations and microbial nitrogen supply and tends to increase apparent total tract digestibility of nutrients.

Table 8. Effects of feeding increasing levels of reduced-oil DDGS to lactating dairy cows on lactation performance, rumen pH, rumen volatile fatty acid and ammonia production, apparent total tract digestibility of nutrients and fecal output (adapted from Castillo-Lopez, 2014)

Measure	0% RO-DDGS	10% RO-DDGS	20% RO-DDGS	30% RO-DDGS
Body weight, kg	687	688	693	697
Body condition score	3.06	3.10	3.14	3.18
Dry matter intake, kg/day	25.0	23.8	25.9	27.9
Milk yield and composition				
Milk yield, kg/day	34.4	33.2	34.5	34.2
Milk fat %	3.59	3.74	3.64	3.67
Milk fat yield, kg/day	1.24	1.23	1.25	1.26
Milk protein %	3.08	3.18	3.15	3.19
Milk protein yield, kg/day	1.06	1.04	1.07	1.09
Milk lactose %	4.80	4.70	4.73	4.73

Table 8. Effects of feeding increasing levels of reduced-oil DDGS to lactating dairy cows on lactation performance, rumen pH, rumen volatile fatty acid and ammonia production, apparent total tract digestibility of nutrients and fecal output (adapted from Castillo-Lopez, 2014)

Measure	0% RO-DDGS	10% RO-DDGS	20% RO-DDGS	30% RO-DDGS
Milk lactose yield, kg/day	1.66	1.58	1.62	1.63
Milk urea nitrogen, mg/dL	16.24	15.54	16.23	15.94
Rumen pH				
Minimum	6.08	6.17	6.06	6.03
Maximum	6.95	8.88	6.83	6.77
Average	6.53	6.49	6.38	6.35
Time < 6.5, minutes/day	546	834	941	1,040
Area < 6.5, pH × minutes/day	126	158	357	334
Time< 6.3, minutes/day	279	382	936	946
Area < 6.3, pH × minutes/day	45	47	180	169
Volatile fatty acids				
Total, mM	136	135	139	131
Acetate, mol/100 mol	63.4	63.4	60.8	60.0
Propionate, mol/100 mol	22.1	22.0	25.0	26.1
Isobutyrate, mol/100 mol	0.8	0.8	0.7	0.7
Butyrate, mol/100 mol	11.2	11.2	10.6	10.7
Isovalerate, mol/100 mol	0.6	0.6	0.6	0.6
Valerate, mol/100 mol	1.8	1.9	2.1	2.2
Acetate:Propionate	2.98	2.94	2.52	2.39
Ammonia, mg/dL	19.0	18.8	19.3	17.6
Nutrient intake, apparent total tract digestibility, and fecal output				
Dry matter digestibility %	65.5	65.4	73.0	73.4
Fecal dry matter, kg/day	6.94	7.20	5.65	5.61
Organic matter intake, kg/day	19.6	19.9	20.0	19.3
Organic matter digestibility %	67.7	67.7	74.9	75.2
Non-fiber carbohydrate intake, kg/day	7.8	7.6	7.4	6.7
Non-fiber carbohydrate digestibility %	89.7	90.1	92.6	92.7
Neutral detergent fiber intake, kg/day	7.0	7.5	7.8	7.9
Neutral detergent fiber digestibility %	44.0	43.2	57.0	58.0
Nitrogen intake, kg/day	0.63	0.63	0.63	0.62
Nitrogen digestibility %	64.3	67.7	74.7	76.9
Fecal nitrogen, kg/day	0.20	0.20	0.15	0.15
Phosphorus intake, g/day	73	86	96	109
Phosphorus digestibility %	28.1	35.0	50.2	50.5
Fecal phosphorus, g/day	46	54	53	53

Ramirez-Ramirez et al. (2016) compared the effects of feeding diets containing 30 percent reduced-oil DDGS (6.6 percent crude fat), with and without 1.9 percent rumen-inert fat and 30 percent conventional high-oil DDGS (12.0 percent crude fat) on rumen fermentation, lactation performance and milk fat composition (Table 9). dry matter intake and milk yield was increased by feeding high-oil and reduced-oil DDGS sources. The increase in dry matter intake was likely a result of the 1.8 times greater proportion of fine particles (less than 1.18 mm) of diets containing DDGS when some of the forage was replaced. As a result, the volatile fatty acid composition of rumen fluid changed when DDGS diets were fed to reduce the concentration of acetate. Milk fat content and yield was reduced by feeding the high-oil DDGS source, but not the 30 percent reduced-oil DDGS diets compared with cows fed the control diet. The predominant bacterial species in the rumen were Bacteroidetes (54 percent) and Firmicutes (43 percent), with a few trends for changes in relative abundance of some bacterial families among dietary treatments. Feeding the DDGS diets resulted in greater polyunsaturated fatty acid intake and lower rumen pH compared with feeding the control diet with no DDGS, which may have been a result in greater fermentability of DDGS in the rumen and less chewing and saliva production during the rumination process. These changes in fermentation caused changes in bacterial biohydrogenation and the formation of conjugated linoleic acid (CLA isomers that suppress milk fat synthesis.) Although trans-10, cis-12 CLA is a known inhibitor of milk fat synthesis, it was only detected in milk from a few cows fed the high-oil DDGS diet, and was not detected in milk from cows fed the other dietary treatments. Furthermore, the concentration and yield of trans-10 18:1 in milk was almost 10 times greater in cows fed the DDGS diets compared with those fed the control diet. Therefore, feeding the reduced-oil DDGS diet appeared to reduce the ruminal supply and production of trans-10 18:1 which is associated with milk fat depression. Furthermore, although feeding the reduced-oil DDGS diet resulted in similar rumen pH compared with feeding the high-oil DDGS diet, there was no reduction in milk fat concentration or yield. This was likely a result of the lower oil content of the reduced-oil DDGS source compared with the conventional high-oil DDGS source. Results from this study showed feeding high-oil and reduced-oil DDGS increases dry matter intake and supported excellent milk production and milk composition even though diets were deficient in forage NDF. Although trans-10, cis-12 CLA was associated with reduced milk fat production, it was not observed when feeding the reduced-oil DDGS diets. Therefore, feeding diets containing 30 percent reduced-oil DDGS reduces the risk of milk fat depression.

Table 9. Effects of feeding total mixed rations containing 30 percent reduced-oil DDGS (6.6 percent crude fat), with or without rumen-inert fat, or 30 percent conventional high-oil DDGS (12 percent crude fat) to lactating dairy cows on lactation performance, milk composition, rumen fermentation, apparent total tract digestibility of nutrients (adapted from Ramirez-Ramirez et al., 2016)

Measure	0% DDGS	30% HO-DDGS	30% RO-DDGS	30% RO-DDGS+RIF
Body weight, kg	607^b	619^a	616^a	619^a
Body condition score	3.1	3.2	3.1	3.2
Dry matter intake, kg/day	21.6^b	25.8^a	26.1^a	26.1^a
Milk yield and composition				
Milk yield, kg/day	32.2^b	33.8^a	33.8^a	34.0^a
3.5% fat-corrected milk[1]	33.2^b	32.8^b	34.3^{ab}	35.0^a
Milk fat %	3.69^a	3.27^b	3.65^a	3.70^a
Milk fat yield, kg/day	1.18^a	1.11^b	1.22^a	1.25^a
Total fatty acids yield, g/day	1,103^a	1,036^b	1,137^a	1,166^a
Total unsaturated fatty acids, g/day	314^c	400^a	365^b	398^a
Total polyunsaturated fatty acids, g/ day	49	79	77	78
Total saturated fatty acids, g/day	787^a	636^b	765^a	766^a
18:1 trans-10	5.6^b	18.9^a	6.4^b	7.6^b
18:2 cis-9, trans-11	4.8^d	13.7^a	9.1^c	11.0^b
18:2 trans-10, cis-12	-	0.05	-	-
Milk protein %	3.07^c	3.22^a	3.21^a	3.12^b

Table 9. Effects of feeding total mixed rations containing 30 percent reduced-oil DDGS (6.6 percent crude fat), with or without rumen-inert fat, or 30 percent conventional high-oil DDGS (12 percent crude fat) to lactating dairy cows on lactation performance, milk composition, rumen fermentation, apparent total tract digestibility of nutrients (adapted from Ramirez-Ramirez et al., 2016)

	0% DDGS	30% HO-DDGS	30% RO-DDGS	30% RO-DDGS+RIF
Milk protein yield, kg/day	1.00^b	1.10^a	1.07^a	1.06^a
Milk urea nitrogen, mg/dL	15.3^b	15.2^b	16.4^a	15.9^a
Rumen fermentation				
pH	6.17^a	5.80^b	5.78^b	6.02^{ab}
Total volatile fatty acids, mM	116	121	127	119
Acetate, mol/100 mol	67.3^a	60.9^c	61.4^{bc}	63.2^b
Propionate, mol/100 mol	18.2^c	23.6^a	23.1^a	20.7^b
Isobutyrate, mol/100 mol	0.85	0.66	0.69	0.76
Butyrate, mol/100 mol	11.6	12.5	12.3	12.8
Isovalerate, mol/100 mol	0.56	0.56	0.51	0.62
Valerate, mol/100 mol	1.62^b	1.84^{ab}	2.00^a	1.91^a
Acetate:Propionate	3.74^a	2.64^c	2.68^{bc}	3.05^b
Ammonia, mg/dL	25.6	28.5	27.4	26.5
Apparent total tract nutrient digestibility				
Dry matter digestibility %	50.6^c	58.0^b	67.1^a	59.1^b
Organic matter digestibility %	52.6^c	59.9^b	69.3^a	60.9^b
Neutral detergent fiber digestibility %	32.5^c	43.8^{ab}	53.0^a	43.2^b
Nitrogen digestibility %	53.2^c	63.8^b	72.6^a	64.4^b

[1] 3.5 percent fat-corrected milk = (milk fat, kg × 16.216) + (milk yield, kg × 0.4324)

Whelen et al. (2017) evaluated feeding a by-product mixture containing equal proportions (11.6 or 31 percent) of soybean hulls, DDGS and palm kernel extract to replace barley and soybean meal in diets for mid-lactation dairy cows grazing perennial ryegrass pasture. Results from this study showed barley and soybean meal can be replaced with soy hulls, DDGS and palm kernel meal without affecting milk production, digestibility and metabolic measures in dairy cows grazing ryegrass pasture.

Consumer satisfaction and health benefits of consuming milk

Several studies have shown feeding DDGS to lactating dairy cows increases the concentration of unsaturated fatty acids in milk, which can potentially lead to peroxidation and the development of off-flavors. Therefore, Testroet et al. (2015) determined the effects of feeding 0, 10, or 25 percent DDGS diets to lactating dairy cows on chemical composition and flavor characteristics of milk. Milk peroxides and free fatty acid content were low and almost all were below the detection limit. Results from this study indicate although feeding DDGS diets altered milk composition, it did not contribute to the development of off-flavors in milk.

In recent years, there has been tremendous interest in improving the human health benefits by increasing compounds with beneficial health effects in milk. One of these substances is cis-9, trans-11 conjugated linoleic acid (CLA), which has been shown to reduce the risk of carcinogenesis and atherosclerosis, and improve immunity. As a result, there have been several attempts to increase CLA content in milk through dietary changes. Anderson et al. (2006) and Sasikala-Appukuttan et al. (2008) showed that feeding diets containing 10 to 20 percent DDGS increased the CLA concentration in milk without affecting dry matter intake, milk yield and milk fat concentration. More recently, Kurokawa et al. (2013) fed diets containing 0, 10 or 20 percent DDGS diets with high neutral detergent fiber content (46 percent) to lactating dairy cows and confirmed feeding DDGS diets increased milk yield and markedly increased CLA content of milk. Therefore, it appears one of the added benefits of feeding DDGS to lactating dairy cows is an improvement in the human health benefits of consuming milk.

Feeding DDGS to Prepubertal Dairy Heifers

The majority of research on feeding DDGS to dairy cattle has focused on mature lactating dairy cows, with limited research on the effects on growth performance and long-term reproductive and lactation performance of dairy heifers. Although previous research has shown feeding DDGS improves reproductive performance of beef heifers (Martin et al., 2007; Engle et al., 2008), limited studies have been conducted with dairy heifers until recently. Anderson et al. (2015a,b) showed dairy heifers fed diets containing high amounts of reduced-oil DDGS (22 percent) and conventional high-oil DDGS (34 percent) had high ADG (0.96 kg/day) and apparent total tract digestibility of nutrients. Furthermore, Anderson et al. (2015b) showed energy status was maintained by feeding high DDGS diets based on similar plasma concentrations of leptin, IGF-1 and insulin, but feeding the high-oil DDGS diet increased plasma cholesterol and fatty acid concentations compared with feeding the reduced-oil DDGS diet. Increases in these plasma lipids may improve reproductive performance (Talavera et al., 1985; Thomas et al., 1997; Funston, 2004). To further evaluate these responses, Anderson et al. (2015c) determined reproductive performance, body measures and subsequent milk production and composition when fed diets containing a control diet based on corn and soybean products, 22 percent reduced-oil DDGS or 34 percent high-oil DDGS diets to 33 prepubertal dairy heifers for 24 weeks until calving, and subsequent four months of lactation. There were no differences in age at first service, number of inseminations, age at conception or calving (Table 10). Heifers fed the high-oil DDGS diet had less wither height and body length compared with those fed the control and reduced-oil DDGS diets. Heifers fed the reduced-oil DDGS diet had greater milk yield than those fed the other diets, and milk protein and fat content and yield were similar among dietary treatments. These results show feeding diets containing either high-oil or reduced-oil DDGS to replace corn and soybean products to prepubertal heifers maintains or enhances reproductive and lactation performance. Furthermore, dietary oil from DDGS can effectively replace starch from corn without detrimental effects on subsequent performance.

Table 10. Reproductive performance, body measures, lactation performance and milk composition of dairy heifers fed diets containing 22 percent reduced-oil DDGS and 34 percent high-oil DDGS for 24 weeks prepartum and four months of subsequent lactation (adapted from Anderson et al., 2015c)

Measure	0% DDGS	22% Reduced-oil DDGS	34% High-oil DDGS
Age at first service, days	394	400	398
No. artificial inseminations	2.11	2.89	1.78
Age at conception, days	455	483	444
Age at first calving, days	733	764	728
Body measurement, 3 weeks prepartum			
Body weight, kg	681	678	638
Withers height, cm	144^a	144^a	140^b
Hip height, cm	147	147	144
Heart girth, cm	206	206	203
Body length, cm	145^a	144^a	140^b
Body condition score	3.4	3.4	3.4
Body measure, at parturition			
Body weight, kg	634	621	590
Body condition score	3.3	3.1	3.2
Calf body weight, kg	40.8	41.6	41.6
No. calving problems	1	2	2
No. successfully transitioned	9	9	9

Table 10. Reproductive performance, body measures, lactation performance and milk composition of dairy heifers fed diets containing 22 percent reduced-oil DDGS and 34 percent high-oil DDGS for 24 weeks prepartum and four months of subsequent lactation (adapted from Anderson et al., 2015c)

	0% DDGS	22% Reduced-oil DDGS	34% High-oil DDGS
Age freshened, days	732	764	728
Milk yield, kg/day	33.0^{b}	36.4^{a}	34.7^{ab}
Energy-corrected milk[1], kg/day	34.4	37.9	35.1
Milk protein %	2.94	3.01	3.03
Milk protein yield, kg/day	0.98	1.08	1.03
Milk fat %	3.98	3.94	3.86
Milk fat yield, kg/day	1.28	1.41	1.28
Somatic cells, × 10^3/mL	53.4	124.4	299.6

^{a,b}Means within row with different superscripts are different (P less than 0.05)

[1] Energy-corrected milk = (0.327 × kg milk) + (12.95 × kg milk fat) + (7.2 × kg milk protein)

Additional studies have also shown consistent benefits of feeding high-oil and reduced-oil DDGS diets to growing dairy heifers. Suarez-Mena (2015) evaluated the effect of different forage-to-concentrate ratios (50:50 or 75:25) and DDGS inclusion rates (0, 7, 14 or 21 percent) on digestibility and rumen fermentation of precision-fed dairy heifer rations. Feeding the diet containing 14 percent DDGS resulted in the highest apparent digestibility of dry matter, organic matter, acid detergent fiber and neutral detergent fiber, but nitrogen retention decreased with increasing diet inclusion rate of DDGS. Molar concentrations of acetate tended to decrease when feeding the high forage diet and as dietary DDGS levels increased, whereas propionate concentrations increased as DDGS levels increased. Furthermore, rumen protozoa count decreased as dietary DDGS level increased. These results indicate feeding diets containing 14 percent DDGS improved nutrient utilization and fermentation in dairy heifers fed diets with different forage-to-concentrate ratios.

Manthey and Anderson (2016) fed dairy heifers either a DDGS or a corn-soybean meal concentrate at 0.8 percent of body weight along with ad libitum access to grass hay on dry matter intake and growth performance. dry matter intake, body weight, ADG and gain:feed were similar between dietary treatments, and there were no differences in hip height, heart girth, hip width and body condition scores. These results indicate heifers fed DDGS at 0.8 percent of body weight with ad libitum access for grass hay had similar growth performance and skeletal frame growth as those fed equal amounts of the corn-soybean meal concentrate and grass hay. In a subsequent study, Manthey et al. (2016) showed limit-feeding diets containing increasing concentrations of DDGS (up to 50 percent) improved gain:feed, apparent total tract digestibility of dry matter and crude protein, while maintaining body frame growth without increasing body condition score.

Manthey and Anderson (2017) conducted two additional studies to determine the effects of limit-feeding peripubertal dairy heifers diets containing DDGS with different forage-to-concentrate ratios (Experiment 1), and feeding DDGS with ad libitum grass hay (Experiment 2), on growth, rumen fermentation, nutrient digestibility, metabolic profile, onset of puberty and subsequent performance. In Experiment 1, Holstein heifers were fed 30 percent (2.65 percent of body weight), 40 percent (2.50 percent of body weight), or 50 percent (2.35 percent of body weight) DDGS, with the remainder of the diet consisting of grass hay and mineral mix. In the second experiment, heifers were fed either a corn-soybean meal or a DDGS concentrate mix (0.8 percent of body weight) and provided ad libitum access to grass hay. Results from these studies showed DDGS can be used to replace up to 50 percent of hay in limit fed diets, or can replace corn and soybean meal when providing ad libitum access to hay, to support satisfactory growth performance, with some changes in metabolic profiles but improvement in nutrient digestibility.

Manthey et al. (2017) also determined the effects of feeding distillers dried grains (30, 40 or 50 percent) in replacement of forage in limit-fed dairy heifer rations on the metabolic profile and onset of puberty. Plasma glucose, insulin, IGF-1, leptin and triglycerides were similar among treatments, but total fatty acids and polyunsaturated fatty acids increased with increasing dietary levels of DDGS. Heifer age and body weight at puberty were not different among dietary treatments. These results showed that feeding increasing dietary inclusion rates of DDGS (up to 50 percent) maintains body energy status without accumulating excess adipose tissue and has no detrimental effects on age or body weight at puberty.

Lastly, Rodriguez-Hernandez (2017) determined if the type and concentration of glucosinolates in carinata meal affected feed preference and intake compared with feeding DDGS or other oilseed meals in dairy heifers. Heifers had the greatest preference for diets containing DDGS, followed by linseed meal, camilina meal and canola meal, with the least preference for carinata meal.

Conclusions

Corn DDGS is an excellent source of energy, protein and phosphorus for lactating dairy cows. Numerous studies have shown corn DDGS can be included in lactating dairy cow diets at levels up to 20 percent, without decreasing dry matter intake, milk production and milk fat and protein content. In fact, inclusion of 20 to 30 percent DDGS supports milk production equal to or greater than diets with no DDGS, without a reduction in milk fat concentration if rations are properly formulated. Furthermore, adding 30 to 50 percent DDGS to developing dairy heifer diets supports excellent growth, reproductive and subsequent lactation performance. Kalscheur et al. (2012b) provided recommended diet inclusion rates of DDGS for dairy cattle and calves in various stages of production and identified key dietary components that need to be managed when formulating DDGS diets (Table 11).

Table 11. Recommended maximum diet inclusion rates of DDGS for dairy cattle (adapted from Kalscheur et al. 2012b)

Production stage	DDGS %	Critical nutrients in diet formulation
Pre-weaned calves	25	Lysine, fiber, crude fat
Growing heifers	30	Crude fat/energy, sulfur
Dry cows	15	Crude fat/energy, sulfur, calcium/phosphorus
Lactating cows	20	Total fat/polyunsaturated fatty acids, physically effective fiber, sulfur, calcium/phosphorus, RUP, lysine

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CHAPTER 18

Reduced-Oil DDGS in Broiler and Layer Diets

Introduction

CORN DDGS IS AN EXCELLENT FEED INGREDIENT for use in broiler and layer diets. Several scientific reviews have been published that include recommended energy and nutrient values for DDGS when formulating broiler and layer diets (Waldroup et al. 2007; Choi et al., 2008; Swiatkiewicz and Korelski, 2008; Bregendahl, 2008; Salim et al., 2010; El-Hack et al., 2015), but these recommendations generally apply for high-oil (greater than 10 percent crude fat) DDGS and not reduced-oil (less than 10 percent crude fat) DDGS. Fortunately, a considerable amount of research has been conducted during the past seven years to determine the apparent metabolizable energy (AME_n) and digestible amino acid content of DDGS with variable crude fat content. Results from these recent studies are summarized in this chapter. The energy and nutritional composition data, and prediction equations used to derive them, are the most current and representative for corn DDGS sources produced in the U.S., and should be used when formulating precision nutrition DDGS diets for broilers and layers.

Corn DDGS contains about 85 percent of the energy value present in corn for poultry, has moderate levels of digestible essential amino acids, and is high in available phosphorus content. Layer and broiler diets can easily contain up to 10 percent DDGS with minimal, if any, formulation adjustments for energy and amino acids. In a literature review conducted 10 years ago, Swiatkiewicz and Korelski (2008) concluded DDGS is an acceptable ingredient for use in poultry diets and can be safely added at levels of 5 to 8 percent in broiler starter diets, and 12 to 15 percent in grower and finisher diets for broilers and laying hens. However, these are conservative dietary inclusion rates and based on formulating diets on a total amino acid basis rather than a digestible amino acid basis. Recent research studies (Shim et al. 2011; Loar et al., 2010; Masa'deh et al. 2011) have shown DDGS can be added to poultry diets at even higher dietary inclusion rates (e.g. greater than 20 percent) as long as accurate energy and digestible amino acid values are used when formulating DDGS diets.

Energy and Digestible Nutrient Content of Reduced-Oil DDGS for Poultry

Energy is the most expensive component of poultry diets, followed by amino acids and phosphorus. Therefore, determining accurate AME_n, digestible amino acids and available or digestible phosphorus values for the DDGS source being fed to poultry, is the most important aspect for maximizing diet inclusion rates and minimizing diet cost, without affecting performance or meat and egg quality. It is well documented that AME_n, digestible amino acid and available phosphorus content varies among DDGS sources. The most successful poultry integrators around the world use precision nutrition approaches to formulate diets based on AME_n or true metabolizable energy (TME), standardized ileal digestible (SID) amino acids and standardized total tract digestible or available phosphorus. Due to the variability in nutrient composition of DDGS among sources, dynamic estimates of AME and digestible amino acids and phosphorus should be used instead of published reference values, which are outdated. This chapter provides the latest "state-of-the-art" approaches for determining dynamic estimates of AME_n, SID amino acids and available phosphorus using prediction equations. These approaches should be used when determining economic and nutritional value in least-cost feed formulation when evaluating various U.S. corn DDGS sources. Use of these prediction equations will provide accurate estimates of these important diet formulation variables that will enable the use of relatively high dietary inclusion rates of DDGS to achieve substantial diet cost savings, while supporting acceptable growth performance and carcass characteristics in broilers, and egg production and egg quality in layers.

Accurate nutritional values for feed ingredients are also essential for determining economic value, including the highest price that can be paid for DDGS to be used in least cost diet formulations, as well as the maximum diet inclusion rates. Tahir and Pesti (2012b) calculated about $160 million in feed costs can be saved by the global poultry industry if the most accurate digestible amino acid database for feed ingredients is used. Use of linear programming in feed formulation software has been widely implemented to determine the optimal feed ingredient mixture to minimize diet cost by setting restrictions (minimum and maximum inclusion rates) of ingredients relative to meeting nutrient requirements. In addition, most commercial feed formulation software provides the capability of sensitivity analysis or "shadow pricing" to determine the highest price at which an individual ingredient would be included in the formula. Using this approach, feed ingredient usage curves can be developed based on ingredient prices and diet inclusion rates in various feed formulas.

Apparent metabolizable energy (AME_n) content and prediction

The NRC (1994) for poultry indicates the AME_n content of DDGS is 2,667 kcal/kg and the TME_n content is 3,330 kcal/kg on a dry matter (dry matter) basis. However, these estimates are derived from conventional high-oil (greater than 10 percent crude fat) DDGS produced in the ethanol industry over 20 years ago. Today, the composition of reduced-oil DDGS is substantially different than the sources previously used to develop the NRC (1994) energy and nutrient composition values. Three recent studies have been conducted to determine the AME_n content of DDGS sources with variable crude fat concentrations (Table 1).

First, the average AME_n value for DDGS reported by Rochell et al. (2011) was 2,678 kcal/kg dry matter, and was similar to the value reported in NRC (1994). However, in the Rochell et al. (2011) study, only one DDGS source contained less than 10 percent crude fat, which corresponded with the lowest AME_n content (Table 1). The range in AME_n content among conventional, high-oil DDGS sources was 2,593 to 3,098 kcal/kg dry matter, which was a difference of 505 kcal/kg dry matter among DDGS sources with similar crude fat content. Although only six DDGS sources were evaluated in this study, the AME_n content was not correlated with gross energy (GE), crude fat, crude protein, starch, ash, and ADF content, but it was negatively associated with total dietary fiber (TDF; r = -0.77) and neutral detergent fiber (NDF; r = -0.83) content. This finding indicates fiber content is more closely associated with AME_n content of DDGS than crude fat content.

In a subsequent study, Meloche et al. (2013) evaluated 15 DDGS sources, of which six of these sources contained less than 10 percent crude fat. The average AME_n content of these DDGS sources was 2,309 kcal/kg dry matter, which was 358 kcal/kg dry matter less than the NRC (1994) value (Table 1). Furthermore, the difference in AME_n content among these 15 DDGS sources was 955 kcal/kg dry matter, and greater than reported in the Rochell et al. (2011) study. The concentration of AME_n ranged from 1,869 to 2,824 kcal/kg dry matter and was positively correlated with GE (r = 0.69) content, and negatively correlated with TDF (r = - 0.56), NDF (r = - 0.52), acid detergent fiber (ADF; r = - 0.52) content, but was not correlated with crude fat, crude protein, starch, or ash content. These correlations (or lack thereof) are consistent with those reported by Rochell et al. (2011), and indicate fiber content of DDGS is more closely associated with AME_n content than crude fat content. Furthermore, these data also indicate one cannot assume a reduction in crude fat content in DDGS results in an increase in crude protein and fiber content because they were not correlated. Collectively, the results from these two studies indicate crude fat content in DDGS is a very poor predictor of AME_n content.

In a third study, Meloche et al. (2014) reported the average AME_n content of DDGS sources evaluated was 2,764 kcal/kg dry matter, which was 97 kcal/kg dry matter greater than NRC (1994) value for broiler chicks (Table 1). When combining data from these three studies, the range in AME_n content among DDGS sources with variable crude fat content was from 1,869 to 3,634 kcal/kg dry matter. This high variability in AME_n content among DDGS sources indicates the use of published book values will not provide reliable AME_n values for use in practical diet formation, and more dynamic approaches are needed. Therefore, Meloche et al. (2013) developed a "best-fit" AME_n prediction equation using chemical composition measures of DDGS:

AME_n kcal/kg dry matter = - 12,282 + (2.60 × GE kcal/kg dry matter) – (40.67 × percent TDF dry matter) + (89.75 × percent Crude Protein dry matter) + (125.80 × percent Starch dry matter) with $R^2 = 0.86$.

Although this equation is highly accurate ($R^2 = 0.86$) in predicting AME_n content of DDGS sources, measurement of gross energy, TDF and starch content is not commonly determined in commercial laboratories. Therefore, these researchers developed an alternative AME_n prediction equation using NDF as the fiber measure instead of TDF:

AME_n kcal/kg dry matter = - 14,322 + (2.69 × GE kcal/kg dry matter) + (117.08 × percent Crude Protein dry matter) + (149.41 × percent Starch dry matter) - (18.30 × percent NDF dry matter) with $R^2 = 0.88$.

This equation resulted in a slight improvement in accuracy ($R^2 = 0.88$) compared with the initial equation, but still requires the determination of gross energy and starch which are often difficult to obtain from analysis provided by commercial laboratories.

Therefore, Meloche et al. (2014) determined the AME_n content of 15 additional DDGS samples that ranged from 5.0 to 14.2 percent crude fat on a dry matter basis, and used these data to validate AME_n prediction equations from Rochell et al. (2011) and Meloche et al. (2013). Although obtaining GE and TDF values from analysis by commercial laboratories is difficult, the best-fit equation with the highest R^2 (0.92) was:

AME_n kcal/kg dry matter = 2,655 - (18.29 × percent NDF) + (44.14 × percent Ether Extract) + (0.21 × GE, kcal/kg) - (10.91 × percent TDF) – (91.08 × percent Ash) with $R^2 = 0.92$ with a prediction accuracy of 321 kcal/kg.

However, if only commonly measured chemical components are available, the following equation can be used, but it has a lower R^2 (0.70), and it is less accurate ($\underline{+}$ 457 kcal/kg) than the previous equation:

Table 1. Gross energy, AMEn, and chemical composition (dry matter basis) of DDGS sources varying in crude fat content (adapted from Rochell et al., 2011; Meloche et al., 2013; and Meloche et al., 2014)

DDGS source	GE, kcal/kg	AMEn, kcal/kg	Crude fat %	Crude protein %	TDF %	NDF %	ADF %	Starch %	Ash %
Rochell et al. (2011)									
4	5,547	3,098	11.7	29.5	35.9	33.4	8.6	4.9	5.4
1	5,434	2,685	10.2	31.9	35.7	40.1	14.4	6.2	4.5
5	5,375	2,593	10.9	29.7	38.1	40.1	10.6	3.5	4.4
3	5,314	2,628	11.5	29.6	30.3	34.6	11.3	7.9	4.2
6	5,174	2,903	11.5	26.5	32.7	27.7	9.8	3.3	4.5
2	5,076	2,146	3.2	34.7	37.2	51.0	15.8	3.0	5.2
Meloche et al. (2013)									
15	5,167	2,687	13.2	30.6	32.4	34.0	9.9	1.3	5.3
14	5,130	2,824	11.8	32.1	33.5	38.9	13.3	1.1	4.9
12	5,077	2,074	11.3	27.7	37.8	44.0	14.0	1.8	4.4
11	5,075	2,418	11.1	29.7	33.9	36.5	12.1	3.9	4.3
9	5,066	2,273	10.8	29.7	35.3	38.6	13.9	1.6	4.6
10	5,043	2,012	10.8	31.0	35.7	38.9	12.9	0.9	4.9
3	5,022	2,487	6.3	28.9	28.5	27.0	8.2	3.3	5.2
13	5,008	2,032	11.5	26.5	32.7	27.7	9.8	3.3	4.5
2	4,990	2,551	4.2	27.9	30.5	27.3	7.7	3.7	4.8
5	4,963	2,401	9.6	30.1	30.8	33.3	10.5	3.4	4.9
6	4,963	2,526	9.7	29.8	31.3	28.8	10.3	2.8	5.0
7	4,948	2,309	10.0	32.3	33.9	35.9	13.7	1.0	5.3
8	4,938	2,068	10.1	30.3	33.9	38.2	12.5	2.2	5.0
4	4,897	2,103	8.6	32.9	32.5	35.7	13.4	0.8	5.1
1	4,678	1,869	3.2	34.7	37.2	51.0	15.8	3.0	5.2
Meloche et al. (2014)									
1	5,254	3,634	13.3	29.7	31.5	38.3	11.5	2.5	4.8
10	5,254	3,120	14.3	33.0	26.5	32.8	12.1	4.0	4.6
6	5,194	2,535	11.4	29.8	32.1	27.8	8.6	4.7	5.5
15	5,154	3,137	11.6	30.7	33.6	33.0	8.2	6.7	5.0
8	5,148	2,640	8.2	34.1	30.5	37.1	13.2	4.0	5.1
2	5,139	2,553	10.4	32.0	31.6	38.5	12.1	2.3	4.7
11	5,098	3,111	12.0	28.4	28.1	38.1	10.7	10.0	4.6
3	5,061	2,869	9.1	31.6	31.1	39.6	11.6	3.8	5.4
14	5,052	2,644	8.8	28.5	36.6	37.1	9.7	5.9	5.4
4	5,009	2,781	8.0	30.6	32.4	31.0	8.9	4.9	5.6
5	4,978	2,523	7.0	32.2	32.8	31.1	8.6	4.4	5.5
9	4,951	2,461	10.7	32.7	29.2	43.8	14.8	8.1	4.7
13	4,934	1,975	6.1	30.3	31.4	32.9	9.2	4.9	5.4
12	4,884	2,581	5.9	32.3	31.7	34.6	9.4	6.0	5.6
7	4,841	2,903	5.0	34.2	29.3	31.4	8.8	5.6	5.6

AME_n kcal/kg dry matter = 3,673 - (121.35 × percent Crude Fiber) + (55.29 × percent Ether Extract) – (121.08 × percent Ash)

Another approach in addition to using prediction equations to dynamically estimate AME_n content among various DDGS sources in precision poultry nutrition programs, a computer-controlled simulated digestion system to predict the concentration of ME in various feedstuffs for roosters was developed by Zhao et al. (2014), and is being used in the feed industry in China. This method provided accurate predictions of AME and TME content for 17 of the 26 feed ingredients evaluated, including corn DDGS.

Digestible amino acid content and prediction

Selection of accurate total and digestible amino acid databases for feed ingredients is also essential for optimizing bird performance and economic value of feed ingredients. The NRC (1994) for poultry has been widely used for many years, but the energy and nutrient content and digestibility of most ingredients have changed dramatically over the past 23 years, especially for DDGS. Therefore, continued use of feed ingredient energy and nutrient values in this outdated reference is not advised.

Feed formulations based on digestible amino acid content of ingredients have been shown to improve growth rate, feed intake and carcass composition of broilers (Rostagno et al., 1995; Fernandez et al., 1995) compared with formulating on a total amino acid basis. Although many poultry nutritionists assume tamino acid digestibility values obtained from rooster assays are similar among various species of birds (i.e. broilers, layers, ducks, and turkeys), Tahir and Pesti (2012a) showed this assumption is incorrect. These researchers showed digestible amino acid values were 6 to 14 percent greater among 20 feed ingredients evaluated when estimates were derived from the rooster assay compared with values from the same ingredients determined using broiler chick assays.

Ajinomoto Heartland (Chicago, IL) and Evonik Degussa (Hanau-Wolfgang, Germany) have developed comprehensive databases for digestible amino acid content for many feed ingredients fed to poultry. However, the distinguishing difference between these databases is that the Ajinomoto values are derived from rooster assays and Evonik values are based on broiler chick assays. As a result, the digestible lysine (0.60 vs. 0.56 percent), methionine (0.47 vs. 0.44 percent), total sulfur amino acids (TSAA; 1.07 vs. 1.00 percent), and threonine (0.72 vs. 0.71 percent) content of DDGS were greater in the Ajinomoto database than in the Evonik database, respectively. Despite the widespread use of both the rooster and chick assays for determining amino acid digestibility in poultry, the accuracy of using digestibility values from these methods on growth performance of birds of various ages and genetic strains remains to be determined (Tahir and Pesti, 2012b). To provide a better understanding of the economic value of DDGS in broiler, turkey and layer diets, Tahir and Pesti (2012b) conducted a comparison of using Ajinomoto and Evonik digestible amino acid databases in common commercial diet formulations (Table 2).

There are several key points to be learned from the comparisons in Table 2:

1. Using average feed ingredient prices from 2009, shadow prices for DDGS inclusion in all feed formulations for broilers, turkeys, and layers exceeded the purchase price for DDGS by \$65.9 to \$139.5/metric ton. This indicates DDGS has much greater value in poultry diets than the market purchase price.

2. Shadow prices of DDGS were greater (\$0.2 to \$6.4/metric ton) when using the Evonik amino acid digestibility database than the database from Ajinomoto, except for turkey finisher and pre-lay layer diets. This difference was due to the lower digestible amino acid values for DDGS in the Evonik database and emphasizes the importance of choosing accurate amino acid digestibility values when making purchasing decisions for DDGS based on shadow pricing.

3. The value of DDGS is not necessarily greater in high cost diets (i.e. turkey starter) compared with lower-cost diets (i.e. turkey finisher).

4. The value of DDGS varies among classes and ages of birds, with the greatest value in pre-lay layers, and the lowest value in turkey starter diets. The economic value of DDGS is greater for finisher diets for broilers and turkeys than for starter diets.

5. At prices between \$221.40 and \$226.70/ton, 7 to 17 percent DDGS would be included in broiler starter diets when using the Evonik amino acid digestibility values, but no DDGS would be used at DDGS prices less than \$221.40/metric ton if Ajinomoto amino acid digestibility values were used. This further emphasizes the importance of using accurate amino acid digestibility values for DDGS when evaluating its value and use in poultry diets.

6. Even greater diet inclusion rates (20 to 24 percent) of DDGS in broiler starter diets could be used based on economics alone, if DDGS prices were between \$211.10 and \$191.20/metric ton in this comparison. This indicates greater diet inclusion rates of DDGS can be achieved when the DDGS price decreases relative to the price of other competing ingredients.

7. Broilers in the finisher phase have lower requirements for the dietary concentration of digestible amino acids than during the starter phase. As a result, differences in amino acid digestibility values among databases are

much less important in diets with relatively low digestible amino acid concentrations than in diets containing high digestible amino acid concentrations, which ultimately affect differences in shadow prices and dietary inclusion rates of DDGS.

Many nutritionists assume as crude fat content of DDGS decreases, the crude protein and amino acid content increases. As shown in Table 3, this is not a valid assumption because this change in composition does not consistently occur among DDGS sources with variable crude fat content. For example, although total lysine and threonine content tended to increase as crude fat content decreased, tryptophan content decreased and methionine content of the 5.4 percent oil DDGS source was the same as the 10.5 percent oil source (Table 3). Apparent ileal amino acid digestibility (AID) for lysine, methionine, threonine and tryptophan was less in reduced-oil DDGS sources compared with the AID 10.5 percent crude fat DDGS source. These results suggest crude fat content of DDGS affects digestibility of some amino acids for poultry (Dozier et al., 2015). However, when considering the combined changes in total concentration and digestibility, there were no differences in apparent ileal digestible lysine, threonine content, small and inconsistent differences in digestible tryptophan content and variable digestible methionine content among these three DDGS sources. These results indicate digestible amino acid content of reduced-oil DDGS sources is not dramatically different than that in high-oil DDGS sources even though digestibility coefficients for several amino acids are reduced. However, methods to dynamically determine digestible amino acid content in DDGS with variable amino acid and crude fat composition are needed.

Table 2. Comparison of DDGS market price versus shadow price in commercial broiler, turkey and layer feed formulations (adapted from Tahir and Peski, 2012b)

		Broiler Starter (Ross)		Broiler Finisher (Cobb)		Turkey Starter (Nicholas)		Turkey Finisher (British United Turkey Males)		Leghorn Prelay (ISA North America)		Leghorn Peak (Hy-Line)	
Ingredient	$/MT	Alin.	Evo.	Alin.	Evo.	Alin.	Evo.	Alin.	Evo.	Alin.	Evo.	Alin.	Evo.
Corn	170	58.41	56.17	71.96	71.20	39.48	36.42	81.22	81.17	59.40	59.16	56.08	54.40
Soybean meal	396	36.37	38.23	21.92	22.54	49.85	52.39	14.80	14.80	20.69	21.25	27.98	29.41
Wheatmiddlings	265	-	-	-	-	-	-	-	-	13.88	13.55	-	-
Poultry grease	487	2.00	2.33	2.70	2.78	5.57	6.03	1.00	1.00	-	-	4.04	4.29
L-lysine	1,666	0.17	0.19	0.18	0.19	0.33	0.35	0.18	0.19	-	-	-	-
DL-methionine	3,721	0.30	0.32	0.19	0.22	0.37	0.40	0.18	0.20	0.15	0.15	0.18	0.21
L-threonine	2,485	0.06	0.08	-	-	0.07	0.09	-	-	-	-	-	-
Limestone	45	0.65	0.65	0.68	0.68	0.73	0.73	0.61	0.61	3.90	3.90	9.08	9.08
Defluorinated phosphate	646	1.70	1.68	2.09	2.08	3.34	3.32	1.41	1.41	1.67	1.66	2.26	2.25
Salt and VTM premix	-	0.36	0.36	0.33	0.33	0.27	0.27	0.67	0.67	0.32	0.32	0.37	0.37
Total diet cost, $/MT		283.5	290.3	249.7	252.6	338.1	347.4	224.6	225.7	241.7	242.8	255.2	260.2
DDGS market price, $/MT	154												
DDGS shadow price, $/MT		221.4	226.7	240.6	240.8	219.9	225.2	236.3	227.6	293.5	291.5	233.8	240.2
Difference betweenDDGS marketpriceand shadow price, $/MT		67.4	72.7	86.6	86.8	65.9	71.2	82.3	73.6	139.5	137.5	79.8	86.2

Alin.= Ajinomoto, Evo.= Evonik

Table 3. Total, apparent ileal digestibility (AID) and apparent ileal digestible amino acid (AIDAA) content of DDGS sources with different concentrations of crude fat (adapted from Dozier et al., 2015)

Nutrient %	10.5% Oil DDGS			7.9% Oil DDGS			5.4% Oil DDGS		
	Total	AID	AID AA	Total	AID	AID AA	Total	AID	AID AA
Moisture	9.3	-	-	10.6	-	-	10.3	-	-
Crude protein	27.9	-	-	27.6	-	-	29.2	-	-
Arginine	1.25	79.9	1.00	1.35	77.6	1.05	1.32	76.2	1.00
Cysteine	0.55	68.4	0.37	0.57	62.9	0.36	0.52	62.0	0.32
Histidine	0.76	75.0	0.57	0.78	71.2	0.56	0.81	72.1	0.58
Isoleucine	1.05	73.3	0.77	1.05	69.8	0.73	1.13	70.2	0.79
Leucine	3.40	83.5	2.84	3.27	80.1	2.62	3.54	80.3	2.84
Lysine	0.81	55.2	0.45	0.87	51.0	0.44	0.89	50.4	0.45
Methionine	0.55	79.1	0.43	0.64	77.8	0.50	0.54	72.2	0.39
Phenylalanine	1.43	79.9	1.15	1.41	76.7	1.09	1.53	76.8	1.18
Threonine	1.08	61.2	0.66	1.11	56.6	0.63	1.16	56.3	0.65
Tryptophan	0.29	76.7	0.15	0.22	73.3	0.16	0.20	70.8	0.14
Valine	1.43	73.3	1.05	1.45	69.9	1.01	1.52	70.1	1.07

Adedokun et al. (2015) determined the standardized ileal digestibility (SID) of amino acids in five sources of DDGS for broilers (21 days of age, Ross 708) and layers (30 weeks of age, Hy-Line W36). The DDGS sources contained 8.25 to 9.79 percent crude fat, and the ranges in the apparent ileal dry matter and crude protein digestibility, as well as the SID of amino acids in the five DDGS sources are shown in Table 4. There was significant variability in digestibility in dry matter, crude, protein and indispensable amino acids among sources with similar crude fat content, with an average of 9.9 percentage points difference in SID amino acid digestibility for layers. As expected, SID lysine coefficients were the most variable (41.3 to 56.5 percent), followed by cysteine (56.8 to 69.0 percent), methionine (67.9 to 78.6 percent), and valine (55.8 to 66.5 percent). Variability of SID of amino acids among the DDGS sources was less for broilers with average difference in coefficients of 7.1 percentage points. Again, the greatest variability in SID coefficients for broilers was for lysine (49.9 to 63.3 percent), followed by isoleucine (67.8 to 76.8 percent), valine (68.5 to 75.9 percent), threonine (61.7 to 69.0 percent), and methionine (77.7 to 85.0 percent). The SID values for lysine and methionine were 8.2 and 7.4 percentage points greater in broilers than layers, respectively. These results suggest different amino acid digestibility coefficients should be used when formulating DDGS diets for layers compared with broilers, and that accurate methods are needed to dynamically estimate SID amino acid content among DDGS sources for poultry. Furthermore, these estimates are the first published SID values for DDGS for layers, and should be used when formulating precision nutrition layer diets.

Because of the high variability in digestible amino acid content among DDGS sources, and the need for methods to dynamically estimate digestible amino acid content, Zhu et al. (2017) conducted a meta-analysis based on 86 observations from 19 publications to develop prediction equations for standardized ileal digestible amino acid values in corn and wheat DDGS for poultry. The overall average chemical composition and coefficient of variation of corn DDGS sources reported in these published studies is shown in Table 5. As expected, there is considerable variation in chemical composition among corn DDGS sources which is important for developing robust prediction equations. Lysine content was the most variable among DDGS sources. The standardized ileal digestibility (SID) was greatest for leucine (85.0 percent) and tryptophan (84.5 percent), and the least for lysine (62.7 percent; Table 6). The average, range and coefficient of variation in standardized ileal digestible amino acid content in corn DDGS among sources is shown in Table 7.

Table 4. Ranges in the apparent ileal dry matter and crude protein digestibility, and SID coefficients (percent) of amino acids in the five corn DDGS sources (adapted from Adedokun et al., 2015)

Nutrient %	Laying hens	Broilers
Dry matter	40.8 – 50.5	42.2 – 51.1
Crude protein	59.6 – 68.3	72.2 – 78.2
Arginine	66.0 – 74.7	76.0 – 82.6
Cysteine	56.8 – 69.0	71.6 – 76.5
Histidine	63.7 – 70.5	70.4 – 75.8
Isoleucine	59.6 – 68.5	67.8 – 76.8
Leucine	72.1 – 80.3	81.8 – 86.0
Lysine	41.3 – 56.5	49.9 – 63.3
Methionine	67.9 – 78.6	77.7 – 85.0
Phenylalanine	71.4 – 78.0	77.2 – 82.5
Threonine	52.8 – 63.8	61.7 – 69.0
Valine	55.8 – 66.5	68.5 – 75.9

Table 5. Chemical composition (percent) of corn distillers dried grains with solubles (DDGS) reported in 19 published studies and used in the prediction of standardized ileal digestible amino acid content (88 percent dry matter basis; adapted from Zhu et al., 2017)

Variable	n	Mean	CV[1] %
Crude protein	59	27.16	11.1
Ash	8	4.66	9.3
Ether extract	24	10.24	27.8
Crude fiber	7	8.10	41.0
Neutral detergent fiber	38	35.66	12.1
Acid detergent fiber	20	9.92	19.4
Essential amino acid			
Arginine	75	1.18	16.5
Cysteine	72	0.50	12.4
Histidine	67	0.70	12.1
Isoleucine	75	1.00	15.9
Leucine	75	3.13	11.5
Lysine	75	0.79	19.9
Methionine	75	0.50	15.8
Phenylalanine	67	1.28	12.5
Threonine	75	1.00	11.2
Tryptophan	51	0.20	19.4
Valine	75	1.33	12.4

[1] Coefficient of variation

Table 6. Average, range, and coefficient of variation in standardized ileal digestibility (SID %) of corn DDGS among sources (adapted from Zhu et al., 2017)

Variable	n	Mean	Minimum	Maximum	CV[1] %
Arginine	75	81.5	53.0	92.6	9.7
Cysteine	67	74.3	49.0	91.9	14.3
Histidine	67	76.3	47.0	89.4	11.4
Isoleucine	75	77.0	52.0	89.4	11.1
Leucine	75	85.0	64.3	93.7	7.3
Lysine	75	62.7	31.3	84.8	19.0
Methionine	75	82.9	53.2	98.4	10.0
Phenylalanine	67	81.6	58.3	91.0	8.3
Threonine	75	70.9	39.2	89.7	12.8
Tryptophan	22	84.5	60.2	92.2	10.7
Valine	75	75.9	48.8	90.6	11.5

[1] Coefficient of variation

Table 7. Average, range, and coefficient of variation in standardized ileal digestible amino acid content in corn DDGS among sources (adapted from Zhu et al., 2017)

Variable	n	Mean	Minimum	Maximum	CV[1] %
Arginine	75	0.96	0.47	1.48	21.1
Cysteine	67	0.37	0.22	0.69	22.0
Histidine	67	0.54	0.29	0.83	19.2
Isoleucine	75	0.77	0.49	1.38	23.1
Leucine	75	2.67	1.90	4.24	15.4
Lysine	75	0.51	0.16	0.84	31.6
Methionine	75	0.42	0.22	0.71	21.7
Phenylalanine	67	1.05	0.70	1.63	17.9
Threonine	75	0.71	0.36	1.10	20.1
Tryptophan	22	0.18	0.08	0.26	26.8
Valine	75	1.02	0.60	1.64	20.6

[1] Coefficient of variation

Total amino acid content was the only chemical component included in standardized ileal amino acid content prediction equations (Table 8) because it was the most predictive variable and represented the majority of the variation among sources. The prediction equations developed had low RMSE (0.01 to 0.36) and high R^2, which explained 84 to 99 percent of the variation in values. The prediction model evaluation showed that the slope and intercept, which represent linear bias and mean bias, respectively, were not significantly different from 0 and 1 for all amino acids, indicating that the equations are highly reliable for predicting SID amino acids in DDGS for poultry (Table 9). The two most commonly used methods for determining amino acid digestibility of feed ingredients for poultry are the standardized ileal amino acid digestibility chick assay using 3-week old broilers and the precision-fed cecectomized rooster assay. However, the amino acid digestibility estimates obtained from using these assays are different, and some nutritionists prefer using data from one of these assays over the other. Therefore, prediction equations were also developed from data in studies using broiler chick assays and precision-fed cecectomized rooster assays (Table 10).

Table 8. Equations to predict standardized ileal digestible amino acid content of sources of DDGS from chemical composition for poultry (adapted from Zhu et al., 2017)

Amino acid	Equation[1]	R^2	RMSE	Prediction Error	Prediction Bias
Arginine	$y = -0.20 + 0.96x$	0.95	0.13	0.19	0.31
Cysteine	$y = -0.07 + 0.88x$	0.87	0.09	0.09	0.29
Histidine	$y = -0.17 + 1.00x$	0.91	0.08	0.10	0.46
Isoleucine	$y = -0.01 + 0.77x$	0.94	0.12	0.20	0.55
Leucine	$y = -0.60 + 1.04x$	0.93	0.36	1.48	2.57
Lysine	$y = -0.22 + 0.91x$	0.87	0.16	0.25	0.25
Methionine	$y = -0.12 + 1.05x$	0.90	0.08	0.06	0.08
Phenylalanine	$y = -0.15 + 0.93x$	0.99	0.06	0.22	> 0.001
Threonine	$y = -0.17 + 0.88x$	0.84	0.24	0.23	0.73
Tryptophan	$y = -0.03 + 1.00x$	0.99	0.01	> 0.001	0.01
Valine	$y = -0.19 + 0.90x$	0.93	0.15	0.40	0.82

[1] y is the predicted standardized ileal digestible amino acid content and x is the total concentration of the amino acid in DDGS.

Table 9. Comparison of observed versus predicted standardized ileal digestible amino acid content of sources of DDGS from chemical composition for poultry (adapted from Zhu et al., 2017)

Amino acid %	Observed Mean	Predicted Mean	Intercept	Standard Error	P value
Arginine	0.97	0.97	0.01	0.02	0.75
Cysteine	0.38	0.37	0.00	0.02	0.98
Histidine	0.54	0.53	0.01	0.02	0.59
Isoleucine	0.79	0.79	0.02	0.02	0.50
Leucine	2.58	2.55	0.06	0.08	0.46
Lysine	0.50	0.50	0.01	0.02	0.69
Methionine	0.42	0.42	0.01	0.01	0.54
Phenylalanine	1.09	1.08	0.03	0.03	0.35
Threonine	0.71	0.71	0.01	0.03	0.84
Tryptophan	0.18	0.18	0.00	0.00	0.30
Valine	1.03	1.02	0.03	0.04	0.45

Table 10. Equations to predict standardized ileal digestible amino acid content of sources of DDGS from chemical composition based on broiler chick assays and cecectomized rooster assays (adapted from Zhu et al., 2017)

	Chick assays			Rooster assays		
Amino acid	Equation[1]	R^2	RMSE	Equation[1]	R^2	RMSE
Arginine	$y = -0.16 + 0.89x$	0.90	0.15	$y = -0.09 + 0.95x$	0.99	0.03
Cysteine	$y = -0.05 + 0.82x$	0.79	0.10	$y = -0.08 + 0.98x$	0.97	0.02
Histidine	$y = -0.24 + 1.06x$	0.88	0.08	$y = -0.08 + 0.95x$	0.99	0.04
Isoleucine	$y = -0.03 + 0.71x$	0.90	0.13	$y = -0.11 + 0.95x$	0.99	0.04
Leucine	$y = -0.79 + 1.08x$	0.87	0.37	$y = -0.12 + 0.94x$	0.98	0.09
Lysine	$y = -0.24 + 0.90x$	0.73	0.21	$y = -0.20 + 0.97x$	0.99	0.05
Methionine	$y = -0.16 + 1.12x$	0.81	0.10	$y = -0.05 + 0.97x$	0.99	0.01
Phenylalanine	$y = -0.19 + 0.95x$	0.76	0.27	$y = -0.13 + 0.98x$	0.98	0.03
Threonine	$y = -0.14 + 0.82x$	0.82	0.13	$y = -0.15 + 0.94x$	0.99	0.04
Tryptophan	$y = -0.08 + 1.13x$	0.99	0.01	$y = -0.01 + 0.92x$	0.98	0.01
Valine	$y = -0.17 + 0.86x$	0.86	0.16	$y = -0.13 + 0.92x$	0.98	0.06

[1] y is the predicted standardized ileal digestible amino acid content and x is the total concentration of the amino acid in DDGS.

Lastly, many commercial feed mills are using near infrared reflectance spectroscopy (NIRS) to quickly and inexpensively obtain nutrient composition data of various feed ingredients to update nutrient composition databases in feed formulation software. Calibrations for total and digestible amino acids in DDGS have been developed for various NIRS equipment. A recent study by Soto et al., (2013) evaluated different strategies for broiler feed formulation when determining amino acid and ME content of feed ingredients. These researchers compared the use of published table values for total amino acids, with total amino acid values obtained from NIRS, digestible amino acid values from NIRS and digestible amino acids and ME values from NIRS in feed formulation and the effects on broiler growth performance and carcass composition. Results from this study showed that using Foss NIRS to determine digestible amino acid and ME content in corn, soybean meal and DDGS, and using these data to formulate diets, resulted in improved body weight gain and feed conversion compared with using total amino acid values from published nutrient composition tables.

Available and digestible phosphorus

Compared with grains and other grain by-products, DDGS contains the greatest concentration of digestible and available phosphorus for poultry. Tahir et al. (2012) reported among multiple samples of corn, soybean meal, bakery by-product meal, wheat, wheat middlings canola meal and wheat shorts, corn DDGS had the lowest phytate and highest non-phytate content among these ingredients. Total phosphorus and phytate content (dry matter basis) of 89 corn DDGS samples averaged 0.96 and 0.26 percent, respectively, which were 124 and 72 percent, respectively, of the values reported in NRC (1994). This indicates that using phosphorus value for DDGS from NRC (1994) will result in underestimation of total phosphorus content and overestimation of phytate and available phosphorus content. These researchers also showed that although phytate phosphorus content of DDGS was positively correlated with Ca concentration, and negatively associated with NDF, ADF, and crude fat content, the development of a best fit regression model resulted in poor prediction ($R^2 = 0.37$) of phytate content, based on proximate analysis composition of DDGS. As a result, no accurate phosphorus digestibility or availability prediction equations have been developed for DDGS for poultry.

In a recent study by Mutucumarana et al. (2014), the true digestible phosphorus content of corn DDGS was determined to be 0.59 percent, which represented about 73 percent of the total phosphorus (Table 11). However, all diets evaluated by Mutucumarana et al. (2014) were deficient in Ca and P, which may have led to an overestimation of phosphorus digestibility because utilization of phytate phosphorus is increased when dietary concentrations of Ca are below the requirement (Mohammed et al., 1991; Tamin and Angel, 2003), and intestinal phytase activity is significantly increased when birds are fed a phosphorus-deficient diet compared with feeding a phosphorus adequate diet (Davies et al., 1970). The results shown in Table 11 indicate the use on nonphytate phosphorus to estimate digestible phosphorus concentration in feed ingredients is not accurate because the digestible phosphorus content in all ingredients was greater than the nonphytate concentrations, and suggests birds can use a portion of nonphytate P.

Table 11. Phosphorus composition and digestibility of wheat, sorghum, soybean meal, and corn DDGS (adapted from Mutucumarana et al., 2014)

Measure %	Wheat	Sorghum	Soybean meal	Corn DDGS
Total P[1]	0.32 (0.37)	0.24 (0.30)	0.65 (0.62)	0.82 (0.72)
Phytate P	0.21	0.18	0.43	0.38
Nonphytate P[1]	0.11 (0.13)	0.06	0.22 (0.22)	0.44 (0.39)
True digestible P	0.15	0.08	0.52	0.59
As percentage of total P				
Phytate P	66	77	67	47
Nonphytate P	35	23	33	53
True digestible P	46	33	80	73

[1] Values in parentheses are from NRC (1994)

The ability of birds to use phytate phosphorus varies depending on the dietary concentration of Ca, P, vitamin D_3, and fiber, as well as the solubility and location of phytate in the ingredient matrix, feed processing and age of the bird (Ravidran et al., 1995; Angel et al., 2002). Martinez-Amezcua et al. (2006) conducted three experiments to evaluate the effectiveness of adding OptiPhos® phytase and citric acid to broiler diets for improving phosphorus availability in DDGS. In one of the experiments, they used a slope-ratio chick growth and tibia ash assay and determined the bioavailability of phosphorus in DDGS was 67 percent. In another experiment, supplemental phytatse and citric acid released from 0.04 to 0.07 percent more phosphorus from DDGS, which suggests both OptiPhos® phytase and citric acid supplementation can be used to increase the availability of phosphorus in DDGS for poultry. Supplemental phytase and citric acid increased the bioavailability of phosphorus in DDGS from 62 to 72 percent.

Wamsley et al. (2013) determined that the availability of phosphorus in the DDGS source they evaluated was between 66 to 68 percent, which is in agreement with the value reported by Martinez-Amezcua et al. (2006). Therefore, until more accurate methods for estimating phosphorus digestibility and availability are developed for poultry, it is reasonable to assume that about 66 percent of the total phosphorus in DDGS is available to birds.

Feeding Reduced-Oil DDGS to Broilers

Growth performance and carcass characteristics

A total of 17 studies have been published since 2010 evaluating growth performance effects of feeding various diet inclusion rates of DDGS to broilers, and the overall results

Table 12. Summary of growth responses from various dietary DDGS inclusion rates on broiler growth performance

DDGS inclusion rate	Feeding period	DDGS Crude fat	Performance effects	Reference
0, 8, 16, 18, 24, 30% 0, 18, 16, 24%	Finisher I - 28 to 42 d Finisher II - 43 to 56 d	7.4%	Feeding 24 percent DDGS diets during the finisher phases had no effect on ADG, feed intake, and feed conversion	Kim et al., 2016
0, 2.7, 5.4, 8.1% 0, 2, 4, 6 %	Starter - 0 to 28 d Finisher – 29 to 42 d	Not reported	Replacing 20 percent soybean meal (4 to 5.4 percent DDGS) improved body weight gain and reduced diet cost.	Gacche et al., 2016
0, 6, 12%	Starter – 0 to 10 d Grower – 11 to 21 d Finisher – 22 to 42 d	6.5% and 5.4%	No effect on overall ADG, ADFI and Gain:Feed regardless of DDGS oil content and diet inclusion rate.	Cortes-Cuevaset al., 2015

Table 12. Summary of growth responses from various dietary DDGS inclusion rates on broiler growth performance

DDGS inclusion rate	Feeding period	DDGS Crude fat	Performance effects	Reference
0, 5, 10%	0 to 35 d	10.5%	No differences in ADG, ADFI, and Gain:Feed when feeding diets containing 10 percent DDGS from up to 35 d of age.	Hassan and Al Aqil, 2015
0, 15%	Starter - 0 to 21 d Grower - 22-42 d	Not reported	Feeding 15 percent DDGS had no effect on ADG, ADFI, and F/G at d 21 and 42 d.	Min et al., 2015
0, 5, 10, 15%	Starter - 0 to 21 d	8.2%	Feeding the 15 percent DDGS diet decreased ADG on d 7 and 14 compared with feeding 0 and 5 percent DDGS, and decreased on d 21 compared with feeding 0 and 10 percent DDGS. FCR was reduced on d 14 when feeding 15 percent DDGS compared with other inclusion rates, but not on d 21.	Campasino et al., 2015
5, 7, 9% or 8, 10, 12%	Starter - 0 to 13 d Grower - 14 to 26 d Finisher - 27 to 33 d	10.5, 7.8, 5.4%	No effect of crude fat content of DDGS source on growth performance. Adding 5, 7, and 9 percent DDGS resulted in greater ADG, feed intake, and improved feed conversion compared with 8, 10, and 12 percent inclusion rates.	Dozier and Hess, 2015
0 or 12% - starter 0 or 18 % - finisher	Starter – 0 to 21 d Finisher – 21 to 42 d	11.0%	No effect on ADG, ADFI and Gain:Feed when feeding 12 percent DDGS in starter and 18 percent DDGS in finisher when feeding isocaloric and isonitrogenous diets.	Swiatkiewicz et al., 2014
10% 20% 20%	Starter – 0 to 17 d Grower – 17 to 35 d Finisher – 35 to 49 d	11%, 4%	No effect of high or low oil DDGS source on ADG, ADFI, and Gain:Feed in starter and grower. ADFI was greater for birds fed low oil DDGS in the overall feeding period, but no differences in ADG and Gain:Feed.	Kubas and Firman, 2014
7%	Starter - 1 to 21 d Finisher - 22 to 48 d	Not reported	NIRS determined AA content improved BW gain compared with using NRC (1994) values for feed ingredients. Using NIRS to determine digestible AA content improved feed conversion at 21 d compared to using total AA.	Soto et al., 2013
0, 10, 20%	Starter – 0 to 18 d	12.5%, 7.5%, 6.7%t	No effect on BW, feed intake, and feed conversion when fed 20 percent DDGS diets regardless of DDGS oil content	Guney et al., 2013
0, 10, 20%	Starter – 7 to 21 d	Not reported	Increasing DDGS inclusion linearly decreased ADG from d 7 to d 14, but no effects were observed for ADFI and Gain:Feed during this period. There was a quadratic effect on ADFI from d 15 to 21, but no differences in ADG and Gain:Feed.	Perez et al., 2011
0, 10, 20%	Starter – 0 to 21 d Finisher – 22 to 42 d	Not reported	Feeding DDGS increased ADFI but decreased ADG and feed conversion from d 1 to 21, and decreased ADFI, ADG, and feed conversion from d 22 to 42. Feeding 10 percent DDGS vs. 20 percent DDGS had no effect on growth performance during d 1 to 21, but improved ADG and feed conversion during d 22 to 42.	Liu et al., 2011

Table 12. Summary of growth responses from various dietary DDGS inclusion rates on broiler growth performance

DDGS inclusion rate	Feeding period	DDGS Crude fat	Performance effects	Reference
0, 8% 0. 7.5, 15, 22.5, 30%	Starter – 0 to 14 d Grower – 14 to 28 d	Not reported	Feeding 8 percent DDGS during the starter phase, and between 7.5 to 15 percent DDGS during the grower phase provided acceptable growth performance.	Loar et al., 2010
0, 5, 10%	0 to 42 d	12.6%	No effect on overall ADG, ADFI, and feed conversion. Extrusion increased amino acid digestibility in corn DDGS.	Oryschak et al., 2010
0, 10, 20, 30, 40, 50 %	Starter – 0 to 14 d Grower – 14 – 35 d Finisher – 35 to 49 d	Not reported	Up to 20 percent DDGS can be included in broiler diets up to 49 d of age with little or no reduction in growth performance if diets are formulated on a digestible amino acid basis. Adding 30 percent DDGS or more will reduce growth performance.	Wang et al., 2008
0, 15, 30 %	Starter - 0 to 14 d Grower – 15 to 35 d Finisher - 36 to 42 d	9.4%	No effects of feeding 15 percent DDGS continuously and alternating between 0 and 15 percent DDGS on ADG, ADFI, and Gain:Feed when diets are formulated on a digestible amino acids basis. Feeding 30 percent DDGS decreased ADG in each phase and overall ADFI.	Wang et al., 2007

are summarized in Table 12. Of these 17 studies, six studies evaluated the effects of feeding reduced-oil DDGS at various inclusion rates to broilers.

Loar et al. (2010) evaluated the effects of adding 0 or 8 percent DDGS to the starter diet (0 to 14 days) and 0, 7.5, 15, 22.5 or 30 percent DDGS to grower diets (14 to 28 days). Feed conversion and mortality rates were not affected by dietary inclusion rate of DDGS, but growth rate was reduced when feeding diets containing more than 15 percent DDGS. However, Shim et al. (2011) fed isonutritional diets containing 0, 8, 16 and 24 percent DDGS using poultry fat as a supplemental energy source, and diets were formulated on a digestible amino acid basis using crystalline amino acids. Body weight gain was improved at the end of the starter phase (d 18) when birds were fed the 8 percent DDGS diet compared with the control diet, and weight gain and gain:feed were similar among dietary DDGS levels at 42 days. Fat pads, breast meat yield and carcass quality were also not different among broilers fed diets containing up to 24 percent DDGS. These results show DDGS can be a good alternative ingredient in diets for broilers at levels up to 24 percent of the diet when diets are formulated on a digestible amino acids basis, without affecting growth performance and carcass or meat quality.

Guney et al. (2013) fed starter and grower diets containing 0, 10 or 20 percent DDGS with variable oil content, and showed no detrimental effects on body weight gain, feed intake, and feed conversion from 0 to 18 days of age (Table 13). In fact, feed conversion was improved when feeding the 10 percent DDGS diet using the DDGS source containing the lowest crude fat content.

Kim et al. (2016) determined the effects of feeding diets containing up to 30 percent reduced-oil (7.4 percent crude fat) DDGS on broiler finisher growth performance and carcass composition from 28 to 42 days of age (Finisher 1; Table 14) and from 43 to 56 days of age (Table 15). During the first finisher phase, there were no differences in body weight gain, feed intake and feed conversion among dietary DDGS inclusion levels except when feeding the 30 percent DDGS diet, which resulted in reduced growth performance. However, there were no differences in carcass weight or carcass fat, fillet, tender and total breast weights among birds fed increasing levels of DDGS in these diets. Similarly during finisher two phase, Kim et al. (2016) showed there were no differences when feeding up to 24 percent reduced-oil DDGS diets on growth performance and carcass composition. Therefore, there is increasing evidence from multiple published studies indicating reduced-oil DDGS can be fed up to 20 percent in starter and grower diets, and up to 24 percent in finisher diets, without affecting growth performance and carcass characteristics. However, diets must be formulated using accurate AME_n and digestible amino acid values for the reduced-oil DDGS sources being fed to achieve acceptable growth performance and carcass characteristics.

Table 13. Effects of adding 0, 10, or 20 percent DDGS containing variable oil content on growth performance of broilers from 0 to 18 days of age (adapted from Guney et al., 2013)

	Control	12.5% Crude Fat DDGS		7.5% Crude Fat DDGS		6.7% Crude Fat DDGS	
Diet inclusion rate	0%	10%	20%	10%	20%	10%	20%
Day 18 body weight, g	596	666	615	607	615	650	598
Day 0-18 feed intake, g/brid/day	53.6	56.0	56.8	54.2	55.9	53.3	56.7
Gain:Feed	1.61	1.51	1.66	1.61	1.63	1.47	1.70

^{a,b,c}Means with different superscripts within row are different (P less than 0.05).

Table 14. Effects of feeding increasing diet concentrations of DDGS containing 7.4 percent crude fat to broilers during the Finisher 1 on growth performance and carcass composition (adapted from Kim et al., 2016)

	Dietary DDGS inclusion rate					
Finisher 1, 28 to 42 days of age	0%	6%	12%	18%	24%	30%
Body weight gain, kg	1.60^{a}	1.64^{a}	1.57^{a}	1.56^{a}	1.56^{a}	1.42^{b}
Feed intake, kg	3.01	3.06	3.05	2.97	2.98	3.00
Gain:Feed	1.84^{b}	1.87^{b}	1.90^{b}	1.89^{b}	1.90^{b}	2.03^{a}
Body weight, 43 days of age, kg	2.63	2.70	2.62	2.72	2.58	2.60
Carcass weight, kg	1.92	1.97	1.91	1.98	1.87	1.87
Carcass yield %	73.5^{a}	73.2^{ab}	73.5^{a}	72.9^{abc}	72.8^{bc}	72.3^{c}
Fat, g	27	28	28	28	25	29
Fillet, g	461	481	471	483	458	461
Tender, g	98	100	98	98	96	94
Total breast, g	559	581	569	581	553	554

^{a,b,c}Means with different superscripts within row are different (P less than 0.05).

Table 15. Effects of feeding increasing diet concentrations of DDGS containing 7.4 percent crude fat to broilers during the Finisher 2 on growth performance and carcass composition (adapted from Kim et al., 2016)

	Dietary DDGS inclusion rate			
Finisher 2, 43 to 56 days of age	0%	8%	16%	24%
Body weight gain, kg	1.45	1.47	1.42	1.44
Feed intake, kg	3.00	3.14	3.02	3.06
Gain:Feed	2.08	2.09	2.07	2.08
Body weight, 57 days of age, kg	4.61	4.67	4.60	4.66
Carcass weight, kg	3.51	3.47	3.49	3.52
Carcass yield %	75.6	75.2	75.7	76.1
Fat, g	79	77	78	80
Fillet, g	976	964	972	988
Tender, g	179	178	180	182
Total breast, g	1,155	1,142	1,152	1,170

^{a,b,c}Means with different superscripts within row are different (P less than 0.05).

To obtain a more detailed analysis of the overall effects of feeding diets containing DDGS to broilers, a meta-analysis was conducted to summarize growth performance data from 19 published studies (Martinez-Amezcua et al., 2006; Wang et al., 2007; Wang et al., 2008; Loar et al., 2010; Olukosi et al., 2010; Oryschak et al., 2010; Liu et al., 2011; Min et al., 2011; Barekatin et al., 2013a, b, c; Guney et al., 2013; Wamsley et al., 2013; Swiatkiewicz et al., 2014; Campasino et al., 2015; Cortes-Cuevas et al., 2015: Hassan and Al Aqil, 2015; Min et al., 2015; Kim et al., 2016). The results from this meta-analysis are shown in Tables 16, 17, and 18.

Feeding DDGS diets has no effect on body weight gain, improved feed intake by 3 percent, and increased gain:feed by 1.5 percent among the 70 observations reported (Table 16). In fact, 73 percent of the observations showed either no change or improved body weight gain, 85 percent of the observations resulted in no change or an improvement in feed intake and gain:feed was unchanged or improved 91 percent of the time (Table 17). Feeding DDGS diets during the starter period improved body weight gain and gain:feed compared with feeding DDGS diets during the finisher period and the overall the feeding period (Table 18). Increasing DDGS levels linearly increased gain:feed by 5.5 percent when feeding diets containing more than 20 percent DDGS, but had minimal effects when feeding diets containing less than 20 percent DDGS. These results suggest DDGS can be effectively used in starter, grower and finisher broiler diets at inclusion rates up to 20 percent, with minimal effects on body weight gain, feed intake and gain:feed.

Table 16. Summary of effects of dietary DDGS inclusion on growth performance of broilers (summary of 19 studies since 2010)[1]

	DDGS – control (expressed as %)					
Item	BW[2] gain	Feed intake	Gain:Feed	Initial BW, g	Final BW, g	Feeding days
Observations	70	70	70	67	67	70
Studies	16	16	16	15	15	16
Mean	2.7	3.0**	1.5**	345	1,812	26
Minimum	-23.4	-6.5	-21.2	25	302	5
Maximum	76.5	50.8	25.1	3,200	4,660	49

**Means differ from 0 (P less than 0.05).

[1] The inverse of pooled standard error of observations was used as a weight factor in the analysis.

[2] BW = body weight

Table 17. Summary of growth performance responses from feeding DDGS diets compared with control diets in broilers (summary of 19 studies since 2010).

		Response to dietary corn DDGS[1]		
Item	N	Increased	Reduced	Not changed
Body weight gain	70	15	19	36
Feed intake	67	22	10	35
Gain:Feed	70	17	6	47

[1] The number of significant and non-significant results.

Table 18. Summary of effects of feeding period and diet inclusion rates of corn DDGS on growth performance of broilers (summary of 19 studies since 2010)[1]

Item	Feeding period			SE	DDGS inclusion rate %			SE
	Starter	Finisher	Total		< 10	10 to 20	> 20	
Observations	26	14	30	-	21	34	15	-
Studies	8	3	7	-	9	14	7	-
BW gain[2]	0.56	-5.42	-5.57	2.70	-0.89	-2.57	-6.97	2.85
Feed intake	0.14	-3.31	-0.25	1.73	1.10	-1.64	-2.87	1.95
Gain:Feed[2]	-0.05	1.59	4.17	1.40	-0.38	0.54	5.54	1.55

[1] The least squares means value were reported. The inverse of pooled standard errors of observations was used as a weight factor in the analysis. The starter phase was from 0-21 days and the finisher phase was from 21-42 or 49 days. If broilers were fed from 0-42 or 49 days, then growth performance for the entire period was used instead of individual phases.

[2] Every percentage unit (percent) increase in dietary DDGS inclusion resulted in a 0.34 percent decrease (relative percentage) in body weight gain and a 0.32 percent increase in Gain:Feed.

Carcass and meat quality

Researchers have consistently observed positive results in carcass and meat quality when DDGS is added to broiler diets. Corzo et al. (2009) fed diets containing 0 or 8 percent DDGS to broilers and observed no differences in meat color, ultimate pH, cooking loss and shear values. Furthermore, there were no differences in meat texture, but consumer preference of flavor and overall acceptability was slightly greater in meat from broilers fed the control diet. However, consumers characterized chicken breasts from both dietary treatments as "moderately liked," and consumers who "moderately" or "very much" liked the chicken breasts could not differentiate breast meat from birds fed the two dietary treatments. There were no differences in sensory characteristics of chicken breasts between the two dietary treatments, but meat from broilers fed the DDGS diet had increased linoleic and polyunsaturated fatty acid content, which may make it more susceptible to peroxidation during long-term storage of fresh meat. Overall, these researchers indicated that feeding 8 percent DDGS diets resulted in high-quality breast and thigh meat with minimal quality differences.

Schilling et al. (2010) fed diets containing 0, 6, 12, 18 and 24 percent DDGS to broilers for 42 days, and yields of high quality breast meat was achieved regardless of dietary DDGS inclusion rate. Thigh meat quality was similar among birds fed diets containing 0 to 12 percent DDGS, but high dietary inclusion rates resulted in thigh meat that was more susceptible to peroxidation.

Oxidative stress and immune function

There is increasing evidence in multiple animal species that DDGS has chemical properties that reduce oxidative stress and improve immune function and health. Corn DDGS contains relatively high concentrations of tocopherols, tocotrienols and xanthophylls known to be potent antioxidants (see Chapter 6 in this handbook). Furthermore, corn DDGS contains about 10 percent residual yeast and yeast cell wall components (mannans, α-glucans, and nucleotides) have been shown to have beneficial health effects on animals (Shurson, 2017).

Min et al. (2015) conducted a study to evaluate the effects of feeding 0 or 15 percent DDGS diets to broilers for six weeks under an immunosuppressive challenge (dexamethasone). Birds subjected to the immune challenge had reduced growth rate and feed conversion, but feeding the DDGS diets had no effect on growth performance. Interestingly, feeding the DDGS diets resulted in reduced serum total antioxidant activity as well as serum and liver total superoxide dismutase activity, but increased serum IgA, IgG, and malondialdehyde of 21-day old broilers. Chicks fed DDGS had a greater relative abundance of mRNA encoding IL-4 and IL-6 than birds fed the control diets, and the immune challenge decreased expression of glutathione peroxidase, IL-6, and IL-10. These results suggest some benefit of improving immune function when feeding DDGS to broilers subjected to an immune challenge.

Feeding Reduced-Oil DDGS to Chicken Layers

A total of 11 studies have been published since 2010 evaluating egg production and quality when feeding diets containing various amounts of DDGS to layers, and the overall results of these studies are summarized in Table 19. Of these 11 studies, five studies evaluated the effects of feeding reduced-oil DDGS at various inclusion rates to layers.

The use of corn DDGS in chicken layer diets has also recently been reviewed by El-Hack et al. (2015). These authors reported that although previously recommended maximum inclusion rates for DDGS has been 10 to 15 percent in layer diets, several studies have shown much greater inclusion rates can be used to achieve acceptable performance and egg quality if appropriate diet formulation adjustments are made, especially for energy and digestible lysine and methionine content. Furthermore, Masa'deh (2011) showed that feeding 30 percent DDGS diets to laying hens saved $31.15/ton and $28.58/ton for phase I and phase II of production compared to layers fed diets containing no DDGS.

Corn DDGS is an excellent source of energy, digestible amino acids, available phosphorus and xanthophylls for layers. Swiatkiewicz et al. (2014a) indicated feeding diets containing up to 20 percent DDGS without affecting bone quality indices of layers. Furthermore, numerous studies have consistently shown feeding increasing dietary levels of DDGS increases egg yolk color because of the xanthophylls (30 to 56 mg/kg; Trupia et al., 2016) naturally present in corn DDGS.

Table 19. Summary of egg production and egg quality responses from feeding various dietary DDGS inclusion rates to laying hens

DDGS inclusion rate	Feeding period	DDGS Crude fat	Performance effects	Reference
0, 10, 20%	21 to 26 weeks of age	Not reported	No effect on egg production, feed intake, egg weight, and hen body weight change. Feeding 20 percent DDGS reduced daily ammonia emissions 24 percent and hydrogen sulfide emissions by 58 percent.	Wu-Haan et al., 2010
0, 5, 10, 15, 20, 25%	24 to 46 weeks of age (Phase 1) 47 to 76 weeks of age (Phase 2)	10.3%	No effect of dietary DDGS level on feed intake, egg production, Haugh units, specific gravity, and overall weight gain. Increasing DDGS inclusion rate decreased egg weight during Phase 1 but not during Phase 2. Yolk color increased with increasing DDGS in the diets, and decreased nitrogen and phosphorus excretion in manure.	Masa'deh et al., 2011
0, 4, 8, 12, 16%	40 to 50 weeks of age	9.7%	Hens fed DDGS diets had slightly less daily feed intake, but there were no differences in egg production, feed conversion, egg mass, and egg weight among dietary DDGS inclusion levels.	Tangendjaja and Wina, 2011
0, 17, 35, 50%	54 weeks of age fed for 24 weeks	10.7%	Up to 50 percent DDGS diets can be fed without affecting egg production, feed intake, feed conversion, egg weight, and egg mass as long as adequate digestible amino acids are provided in diets containing DDGS. Feeding DDGS diets improved internal quality of eggs during storage and improved egg yolk color. Haugh unit was highest when feeding the 50 percent DDGS diets but there were no differences in yolk and albumen percentage among dietary treatments.	Sun et al., 2012
10 percent		12.2%	No effect on egg production, feed intake, feed efficiency, initial and final body weight, egg weight, egg mass, egg shell thickness, egg shell breaking strength, Haugh unit, damaged eggs, and marketable eggs.	Deniz et al., 2013a

Table 19. Summary of egg production and egg quality responses from feeding various dietary DDGS inclusion rates to laying hens

DDGS inclusion rate	Feeding period	DDGS Crude fat	Performance effects	Reference
0, 5, 10, 15, 20%	28 to 36 weeks of age	11.2%	No effects of feeding up to 15 percent DDGS diets on egg production, feed intake, feed conversion, egg weight, egg mass, damaged eggs, and marketable eggs, but feeding 20 percent DDGS diets reduced performance and egg weight and mass. No effects of DDGS inclusion rate on egg shell thickness andd egg shell breaking strength, Haugh units, but increased yolk color.	Deniz et al., 2013b
0, 10, 20%	40 to 63 weeks of age	8.3%	No effect on egg production, feed intake, egg weight, and egg mass, and yolk color, egg shell thickness, and feed conversion improved with increasing dietary DDGS level.	Jiang et al., 2013
20%	20 to 33 weeks of age	10.3, 7.3, or 5.2%	Crude fat content of DDGS had no effect on egg production, feed intake, feed conversion, egg weight or mass, and hen weight gain.	Purdum et al., 2014
20%	26 to 39 weeks of age (Phase 1) 40 to 55 weeks of age (Phase 2)	11%	No differences in egg production, feed intake, feed conversion, egg weight and mass, internal egg and egg shell quality within layer phase and overall. Feeding DDGS diets increased egg yolk color.	Swiatkiewicz et al., 2014b
0, 6, 12%	69 to 77 weeks of age	6.5 or 5.4%	No difference in egg production, feed intake, feed conversion, egg weight, and egg mass among dietary treatments. Yolk color was improved in DDGS diets.	Cortes-Cuevas et al., 2015
0, 5, 10, 20%	30 to 42 weeks of age	9%	No effect of dietary DDGS level on egg production, egg weight, egg mass, feed consumption, feed conversion per egg mass, egg specific gravity, haugh units, and egg yolk color. Hens fed the 20 percent DDGS diets had greater body weight loss than other treatments.	Hassan and Al Aqil, 2015

To obtain a more detailed analysis of the overall effects of feeding diets containing DDGS to layers, a meta-analysis was conducted to summarize egg production and quality characteristics using data reported from 17 published studies since 2010 (Świątkiewicz and Koreleski, 2006; Shalash et al., 2010; Wu-Haan et al., 2010; Ghazalah et al., 2011; Masa'deh et al., 2011; Tangendjaja and Wina, 2011; Koksal et al., 2012; Sun et al., 2012; Cho et al., 2013; Deniz et al., 2013a; Deniz et al., 2013b; Jiang et al., 2013; Świątkiewicz et al., 2013; Purdum et al., 2014; Cortes-Cuevas et al., 2015; Hassan and Al Aquil, 2015; Trupia et al., 2016).

As shown in Table 20, layers fed DDGS diets lost an average of about 16 percent of body weight when fed DDGS diets compared with those fed the control diets, but feed intake, gain:feed, egg production, egg weight, and Haugh units of eggs were minimally (-0.2 to 2.7 percent change relative to control) affected. However, egg shell thickness and yolk color were positively affected (improved by 4.1 and 18.1 percent, respectively) by feeding DDGS diets to layers. The majority of observations reported in these 17 studies showed either an improvement or no change (Table 21) in hen body weight change (78 percent), feed intake (78 percent), gain:feed (65 percent), egg production (70 percent), egg weight (75 percent), egg shell thickness (100 percent), yolk color (98 percent), and Haugh units (89 percent).

Body weight change and feed intake were similar for hens fed DDGS diets for more than 16 weeks compared with those fed less DDGS diets for than 16 weeks, but gain:feed was greater (P less than 0.01) in studies where layers were fed diets for less than 16 weeks (Table 22). Length of feeding period had no effect on egg production, egg shell thickness and yolk color, but hens fed DDGS diets for less than 16 weeks had a slightly greater (P less than 0.01), but a relatively small (4 percent), reduction in egg weight and a slight improvement (P less than 0.03) in Haugh units compared with layers fed DDGS diets for more than 16 weeks. Increasing diet inclusion rates of DDGS tended (P less than 0.11) to increase body weight change, improved (P less than 0.01) feed intake and increased (P less than 0.01) gain:feed. Furthermore, increasing dietary DDGS inclusion rates decreased (P less than 0.01) egg production and egg weight, but improved (P less than 0.01) Haugh units. Finally, increasing DDGS inclusion rate in laying hen diets tended (P less than 0.11) to improve egg yolk color but slightly reduced egg shell thickness.

Table 20. Summary of effects of feeding corn DDGS diets to laying hens on egg production performance (summary of 17 studies published since 2010)[1]

			DDGS- control (expressed as percent)		
Item	Observations	Studies	Mean	Minimum	Maximum
Body weight change	36	8	-16.0**	-100.0	183.9
ADFI	65	16	-0.2*	-11.7	6.9
Gain:Feed	51	13	2.7**	-4.0	26.1
Egg production	57	15	-1.7**	-28.7	2.6
Egg weight	69	17	-0.5**	-5.5	3.7
Egg shell thickness	32	9	4.1**	-2.8	8.3
Yolk color	41	11	18.1**	-2.3	58.2
Haugh unit	35	9	-0.1**	-2.4	6.0

**Means differ from 0 (P less than 0.05)

*Means differ from 0 (P less than 0.10).

[1]The inverse of pooled standard errors of observations were used as a weight factor.

Table 21. Summary of effects of feeding corn DDGS diets to laying hens on egg production performance (summary of 17 studies published since 2010)[1]

		Response to dietary corn DDGS1		
Item	N	Increased	Reduced	Not changed
Body weight change	36	1	8	27
ADFI	65	2	14	49
Gain:Feed	51	18	2	31
Egg production	57	5	17	35
Egg weight	69	4	17	48
Egg shell thickness	32	6	0	26
Yolk color	41	33	1	7
Haugh unit	35	0	4	31

[1]The number of significant and non-significant results.

Table 22. Summary of effects of length of feeding period and dietary inclusion rate of corn DDGS fed to laying hens on egg production performance and egg quality (summary of 17 studies published since 2010)[1]

	Feeding period			Level of DDGS inclusion %			
Item	> 16 wk	< 16 wk	SEM2	< 10	10 to 20	> 20	SEM
Observations	25	44		16	30	23	
Studies	6	11		9	13	12	
BW change	-28.8	-25.6	17.7	-17.2	-17.5	-46.9	4.9
ADFI	0.03	1.0	0.7	-0.4	0.6	1.4	0.3
Gain:Feed	3.6	13.1	2.9	2.2	7.6	15.1	1.0
Egg production	-4.3	-6.6	1.9	-2.2	-5.6	-8.4	0.8
Egg weight	-2.3	-4.3	0.8	-1.3	-3.5	-5.0	0.3
Egg shell thickness	2.0	-0.8	2.0	1.1	1.0	-0.2	0.6
Yolk color	22.3	23.1	5.2	12.5	16.3	39.3	1.9
Haugh unit	1.5	0.1	0.6	-0.1	1.3	1.2	0.2

[1] The inverse of pooled standard errors of observations were used as a weight factor.

SEM = standard error of mean

Egg quality

As summarized in Table 19, the majority of recent studies evaluating DDGS inclusion rate and crude fat content reported minimal, if any effects on egg quality at relatively high (greater than 20 percent) DDGS inclusion rates. Sun et al. (2012) fed isocaloric diets containing 0, 17, 35 or 50 percent corn DDGS (10.7 percent crude fat) to 54-week old White Leghorn laying hens for 24 weeks to evaluate egg production and internal egg quality. Egg production, feed intake, feed conversion, egg weight and egg mass were reduced only when feeding the 50 percent DDGS diet during the first 12-week period (Table 23). However, once the diets were reformulated to contain increased lysine and methionine content, the reduction in performance from feeding the 50 percent DDGS diet was greatly improved. As a result, there were no differences in egg production, egg weight, and feed intake among dietary treatments during the last six weeks of the study. Feeding increasing dietary levels of DDGS increased egg yolk color and Haugh units, and feeding the 50 percent DDGS resulted in the highest Haugh units indicating eggs produced from hens fed this diet had longer shelf life than eggs from hens fed lower dietary inclusion rates of DDGS (Table 24). Furthermore, shell weight percentage and shell breaking strength were greatest for hens fed the 50 percent DDGS diet. These researchers concluded up to 50 percent DDGS can be added to layer diets without affecting egg production, feed intake, feed efficiency, egg weight and egg mass if sufficient amounts of digestible amino acids are present in DDGS diets.

Table 23. Effect of feeding diets containing increasing levels of DDGS to laying hens on egg production performance during a 24-week feeding period (adapted from Sun et al., 2012)

Measure	0% DDGS	17% DDGS	35% DDGS	50%DDGS
Egg production %	87^{a}	83^{b}	$84^{a,b}$	62^{c}
Feed intake, g/hen/day	104.4^{a}	104.2^{a}	106.0^{a}	92.2^{b}
Feed efficiency, g egg/kg feed	531.6^{a}	487.6^{b}	501.9^{b}	431.8^{c}
Egg weight, g	64.7^{a}	63.3^{bc}	64.0^{ab}	62.6^{c}
Egg mass, g/hn/day	56.0^{a}	51.8^{b}	53.6^{ab}	39.1^{c}
Body weight change, kg	0.02	0.00	0.00	0.05

[a,b,c] Means with different superscripts within row are different (P less than 0.05).

Table 24. Effect of feeding diets containing increasing levels of DDGS to laying hens on egg quality and composition (adapted from Sun et al., 2012)

Measure	0% DDGS	17% DDGS	35% DDGS	50%DDGS
Yolk color[1]	5.5^{d}	7.0^{c}	7.9^{b}	8.7^{a}
Yolk %	26.5	26.8	26.8	26.5
Albumen %	63.7	63.4	63.4	63.3
Shell %	9.8^{b}	9.8^{b}	9.9^{b}	10.1^{a}
Haugh unit[2] storage time, weeks				
Week 0	80.5^{b}	81.8^{b}	82.3^{b}	85.3^{a}
Week 1	76.4^{b}	78.0^{b}	78.3^{b}	82.3^{a}
Week 2	73.7^{b}	75.6^{b}	76.0^{b}	79.9^{a}
Week 3	72.4^{b}	73.7^{b}	74.3^{b}	78.2^{a}
Shell breaking strength, g	$3{,}924^{b}$	$3{,}995^{b}$	$3{,}877^{b}$	$4{,}299^{a}$

[a,b,c,d] ry mattereans with different superscripts withing a row are different (P less than 0.05)

[1] Yolk color score ranges from 1 (light) to 10 (dark).

[2] Haugh unit equation = $100 \times \log [\text{height} - 0.01 \times 5.6745 \times (30 \times \text{weight}^{0.37} - 100) + 1.9]$

Using eggs from the same study, Sun et al. (2013) evaluated the effects of feeding isocaloric diets containing 0, 17, 35 or 50 percent corn DDGS (10.7 percent crude fat) to laying hens on egg yolk composition. There were no differences in egg yolk lipid and protein content except when feeding the 50 percent DDGS diet, which resulted in a slight increase in lipid content and a slight decrease in protein content. Moisture content of eggs was not affected by dietary DDGS inclusion rate. However, increasing dietary DDGS content increased total polyunsaturated fatty acid content of egg yolks, and although choline and cholesterol content were initially greater in yolks from hens fed the 50 percent DDGS diet, the concentrations of choline and cholesterol were not different among diets during the last four weeks of the study. As expected, feeding increasing dietary levels of DDGS increased lutein content of egg yolks. However, an interesting finding in this study was that feeding the 50 percent DDGS diet increased the concentration of omega-3 fatty acids (linolenic acid and eicosapentaenoic acid) in egg yolks, which have been shown to have important health benefits for humans.

Trupia et al. (2016) evaluated the effects of feeding diets containing 0, 10 or 20 percent high-oil (13.3 percent crude fat) or reduced-oil (7.4 percent crude fat) DDGS sources on egg production performance and egg quality, and showed no effects on hen weight gain, egg production, feed intake, feed efficiency, egg mass or egg weight among dietary treatments. Specific gravity of eggs was slightly less for hens fed the 10 percent high-oil or 20 percent reduced-oil DDGS diets. However, eggs from hens fed DDGS diets had greater concentrations of tocopherols, tocotrienols, and xanthophylls in egg yolks and increased yellow and red color compared with layers fed the control diet (Table 25).

The lipid composition of high-oil and reduced-oil DDGS sources fed in this study is shown in Table 26, and indicate the concentrations of tocopherols, tocotrienols and xanthophylls in the DDGS sources fed influenced the composition of these components in egg yolks. In fact, eggs from hens fed the reduced-oil DDGS diet had greater tocopherol content, but lower xanthophyll content than those fed the high-oil DDGS diets. Feeding DDGS slightly altered the fatty acid composition in eggs, but the ratio of saturated to unsaturated fatty acids was similar, with no effect on lecithin or cholesterol content of eggs. These results indicate adding high-oil and reduced-oil DDGS to laying hen diets increases several beneficial lipophilic nutrients in egg yolks and has no apparent detrimental effects on egg yolk quality.

Table 25. Color and lipid composition of egg yolks from laying hens fed 10 or 20 percent high-oil (HO) and reduced-oil (RO) DDGS diets (adapted from Trupia et al., 2016)

Measurement	Control	10% HO DDGS	20% HO DDGS	10% RO DDGS	20%RO DDGS
Yolk L*	58.5^{a}	57.8^{b}	56.7^{c}	57.3^{b}	56.6^{c}
Yolk a*	-4.3^{d}	-3.5^{c}	-2.2^{a}	-3.5^{c}	-2.7^{b}
Fatty acid content %					
C16:0	25.5	25.4	25.1	25.5	25.5
C16:1	2.71^{a}	2.46^{b}	2.08^{c}	2.54^{ab}	2.49^{ab}
C18:0	9.50	9.42	9.56	9.28	9.19
C18:1	45.7^{a}	43.5^{bc}	42.1^{d}	44.4^{b}	42.3^{cd}
C18:2	13.6^{c}	16.4^{b}	18.3^{a}	15.5^{b}	17.6^{a}
C18:3	0.44^{c}	0.45^{d}	0.47^{c}	0.45^{b}	0.58^{a}
C22:0	2.10	2.10	2.20	2.10	2.10
Tocopherols and tocotrienols, µg/g oil					
α-tocopherol	173.8^{b}	183.5^{ab}	183.3^{ab}	209.9^{ab}	218.2^{a}
β-tocopherol	0.58^{c}	0.95^{b}	0.96^{b}	0.98^{b}	1.34^{a}
γ-tocopherol	46.0^{d}	57.2^{cd}	72.2^{ab}	67.0^{bc}	85.1^{a}
δ-tocopherol	$1.1^{a,b}$	1.0^{ab}	0.82^{b}	1.0^{ab}	1.2^{a}
α-tocotrienol	2.5^{c}	4.0^{bc}	5.8^{a}	5.1^{ab}	6.3^{a}
γ-tocotrienol	0.13^{b}	0.23^{ab}	0.34^{a}	0.26^{a}	0.32^{a}
Total tocotrienols	224.2^{c}	246.9^{bc}	263.4^{abc}	284.2^{ab}	312.4^{a}
Xanthophylls, µg/g oil					
Lutein	80.0^{b}	110.1^{a}	123.1^{a}	87.4^{b}	91.1^{b}
Zeaxanthin	22.4^{c}	31.7^{ab}	36.8^{a}	29.1^{b}	34.9^{a}
β-cryptoxanthin	Not detected	1.1^{b}	2.0^{a}	1.0^{b}	1.7^{a}
Unknown	8.6^{d}	13.6^{bc}	17.3^{a}	12.1^{c}	14.8^{ab}
Total xanthophylls	111.1^{d}	156.4^{ab}	179.1^{a}	129.7^{cd}	142.6^{bc}

[a,b,c,d]ry mattereans within rows with different superscripts are different (P less than 0.05).

Table 26. Lipid composition of high-oil (13.3 percent) and reduced-oil (7.4 percent) DDGS added to laying hen diets (adapted from Trupia et al., 2016)

Component	13.3% crude fat DDGS	7.4% crude fat DDGS
Fatty acids % of lipid		
C16:0	11.3	11.9
C16:1	0.14	0.13
C18:0	1.73	1.93
C18:1	27.0	27.4
C18:2	57.7	56.3
C18:3	1.50	1.60
Other lipids, mg/kg		
α-tocopherol	20.9	20.1
β-tocopherol	0.45	0.37
γ-tocopherol	76.0	38.3
δ-tocopherol	1.4	0.9
α-tocotrienol	10.9	8.8
γ-tocotrienol	17.4	9.0
δ-tocotrienol	1.40	0.3
Total tocopherols and tocotrienols	128.6	77.8
Lutein	15.7	39.3
Zeaxanthin	9.4	9.7
β-cryptoxanthin	3.3	3.4
Unknown	1.6	3.7
Total xanthophylls	29.9	56.1

Risk of virginiamycin residues in eggs

Small amounts of antibiotics (1 to 2 mg/kg) are often added to fermenters during ethanol and DDGS production to prevent bacterial infections which reduce ethanol yield and result in reduced DDGS quality and nutritional value. The most common antibiotics used in the U.S. ethanol industry are virginiamycin and penicillin. Paulus-Compart (2013) showed the risk of virginiamycin and penicillin residues in DDGS is very low, and if present, they are at such low concentrations they cannot be detected in meat, milk and eggs. Sun et al. (2012) used plate and bio-autography methods to determine the presence of virginiamycin residues in four diets containing 0, 17, 35 or 50 percent DDGS, and found that virginiamycin residues in all diets were below the 0.1 mg/kg restriction limit, and were barely at the 0.05 to 0.1 mg/kg detection limits of these assays. However, the only FDA-approved method for detecting virginiamycin in feed ingredients and eggs is a bioassay. Therefore, the validity of the results reported is questionable. Regardless, these results suggest the possibility of virginiamycin being present in egg yolk, even when DDGS is added at 50 percent to layer diets, is negligible.

Effects of DDGS on molting

Hong et al. (2007) conducted a study to compare feeding a DDGS diet and a non-salt diet to induce molting and compare the effect of feeding-molting and fasting-molting treatments on egg production performance, egg quality and visceral organ weights of laying hens. They used 108 White Leghorn hens (62 weeks of age) with egg production greater than 80 percent and average body weight of 1.08 kg in this study. The dietary treatments consisted of: control (non-molt treatment) feeding-molting treatment (DDGS and non-salt diet) and fasting-molting treatment. Egg production decreased to 0 percent after 18 days in the feeding-molting group, and decreased to 0 percent after 17 days in the DDGS-non-salt feeding-molting group. Egg production stopped for six days in the fasting-molting group. Egg production restarted after 12 and 16 days in the feeding-molting and fasting-molting groups, respectively. Except for egg yolk quality, egg quality was improved for all molting treatments. Liver, heart and oviduct weights of laying hens decreased with all molting treatments. These results indicate that the feeding-molting treatment (DDGS and non-salt diet) could replace the fasting-molting treatment and reduce animal welfare concerns due to fasting during the molting process.

Mejia et al. (2010) fed 36, 45 and 54 grams/day of DDGS in a non-feed withdrawal molting program, compared with feeding similar daily intakes of corn, and found that post-molt egg production (5 to 43 weeks) was greater for hens fed the DDGS molting diets compared to those fed the corn diets. No consistent differences were observed for egg mass, egg specific gravity, feed efficiency or layer feed consumption among the dietary molting treatments for the post-molt period. These researchers concluded that limit feeding corn or DDGS in a non-feed withdrawal program will result in long-term, post-molt performance comparable to ad libitum feeding of a corn-soybean hulls diet.

Wet litter

One of the concerns in managing commercial broiler and layers facilities is minimizing the occurrence of wet litter. Wet litter has been characterized as a consequence of disturbed water balance in birds (Collett, 2012). Many dietary factors can contribute to the occurrence of wet litter including feeding diets containing a high proportion of non-starch polysaccharides, animal protein, saturated free fatty acids, anti-nutritional factors or toxins (Collett, 2012).

High concentrations of sodium, magnesium or sulfate in drinking water and feed are associated with wet litter problems. Maximum acceptable concentrations of sodium (0.05 g/kg, Muirhead, 1995 to 0.25 g/kg, Coetzee, 2005), magnesium (0.125 g/kg, Schwartz, 1994 to 0.25 g/kg, Coetzee, 2005), and sulfate (0.06 g/kg, Keshavarz, 1987 to 0.50 g/kg, Coetzee, 2005) in drinking water for poultry have been reported. Salt is a common contaminant of drinking water around the world, and should be monitored to make appropriate dietary adjustments in supplemental salt content if necessary. Corn DDGS contains variable, and sometimes high sodium (greater than 0.5 percent) and sulfur (greater than 0.6 percent) content which may contribute to wet litter problems if dietary cation-anion difference and supplemental dietary salt levels are not adjusted in diets containing high inclusion rates of DDGS.

Conclusions

Corn DDGS is an excellent feed ingredient for use in broiler and layer diets to reduce feed cost and provide optimal growth performance, egg production, as well as meat and egg quality. The greatest challenge in using DDGS in poultry diets is to use accurate AME_n, digestible amino acid and available phosphorus values for the DDGS source being fed because energy and digestible nutrient content varies among sources. Crude fat content of DDGS is a poor predictor of AME_n and digestible amino acid content. As a result, prediction equations have been developed to accurately estimate actual AME_n and standardized ileal digestible amino acid content of DDGS sources based on chemical composition. As expected, growth responses and carcass composition of broilers among published studies are variable, but the majority of the responses reported showed either no change or an improvement in common production and carcass composition measurements. In fact, recent studies have shown feeding starter broiler diets containing 20 percent reduced-oil DDGS, and finisher diets containing 24 percent reduced-oil DDGS provides acceptable growth performance and carcass quality. Similarly, egg production and egg quality responses of laying hens among published studies are variable, but the majority of the responses reported showed either no change or an improvement in common egg production performance and egg quality measurements. When using accurate AME_n and digestible amino acid values for reduced-oil DDGS in precision nutrition diet formulations for layers, up to 50 percent corn DDGS diets can be fed to layers to achieve acceptable egg production and egg quality.

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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 b-glucanase activity, starch, total and soluble b-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, b-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/m^3	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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CHAPTER 20

DDGS in Duck and Geese Diets

Introduction

GLOBAL DUCK AND GOOSE PRODUCTION CONTINUES TO INCREASE, especially in Asia countries (The Poultry Site a,b). World meat duck production was 4.4 million tons in 2013, with 83.8 percent produced in Asia (The Poultry Site, 2015a). China is the world's leader in meat duck production (2.9 million tons) followed by Malaysia (129,600 tons), Myanmar (107,000 tons), Vietnam (102,500 tons), Thailand (89,900 tons), South Korea (69,400 tons), and Taiwan (64,000 tons). The primary duck species used to produce duck meat are Pekin, Muscovy (France) and mule ducks (hybrid cross for production of fois gras). The major duck species used for egg production are Jinding and Shao ducks in China; Tsaiya ducks in Taiwan; Khaki Campbell, Indian runner, and Desi ducks in Vietnam, Cambodia and Indonesia (Pingel, 2004). About 37 percent of total egg production in Thailand is derived from duck eggs, followed by Cambodia (21 percent), Indonesia (19 percent), Bangladesh (16 percent), China (15 percent) and the Philippines (12 percent; Pingel, 2004).

Global goose meat production was 2.7 million tons in 2013 (The Poultry Site, 2015b), with Asia accounting for 96 percent (2.6 million tons). Similar to meat ducks, China is the leading producer of goose meat (2.55 million tons), followed by Taiwan (19,550 tons) and Myanmar (6,840 tons).

Unfortunately, very few research studies have been conducted to evaluate DDGS in meat and layer duck diets or meat and layer goose diets. However, the purpose of this chapter is to provide a summary of published information on feeding DDGS to ducks and geese.

Ducks

Meat ducks

Nutrient requirements of ducks are not well established because there are many types of ducks used in various countries (Creswell, 2012). Therefore, without accurate knowledge of nutrient requirements, it is difficult to properly formulate diets to achieve optimal performance. Furthermore, knowledge of the metabolizable energy and digestible amino acid content of commonly used feed ingredients (including DDGS) makes it even more difficult to accurately formulate duck diets. Baéza (2015) conducted an excellent overview of the nutritional requirements and feeding management of meat type ducks (Table 1). Baéza suggested that the optimal levels of crude protein in starter, grower and finisher diets for mule ducks are 23.5, 15.4 and 13.8 percent respectively. Baéza (2015) also indicated that AME requirement for optimal weight gain and feed conversion in Pekin ducks (two to six weeks of age) is about 3,000 kcal/kg, but dietary levels greater than 2,700 kcal/kg of AME increase abdominal fat.

Wen et al. (2017) determined the energy and lysine requirements for Pekin ducks from hatch to 21 days of age, and estimated that the lysine requirements (based on weight gain) were 0.94 and 0.98 percent for diets containing 2,750 and 3,050 kcal/kg AME, respectively. Kong and Adeola (2010) determined the apparent ileal digestibility in DDGS and other feedstuffs for White Pekin ducks (Table 2). As expected, soybean meal had the greatest nitrogen and apparent amino acid digestibility compared with DDGS, corn and wheat. However, apparent digestibility of lysine was lowest in DDGS compared with these other feed ingredients, and have been due to excessive heating during the drying process.

Creswell (2012) suggested that corn DDGS can be used up to 10 to 15 percent in duck diets, but Kowalczyk et al. (2012) showed that feeding diets containing up to 25 percent DDGS for Pekin ducks between 22 to 56 days of age had no negative effects on growth performance, carcass composition or chemical composition, pH, and color of breast meat. Similarly, Peilod et al. (2010) showed that adding 24 percent DDGS to growing and finishing diets for mule ducks had no negative effects on growth performance.

Adamski et al. (2011) evaluated the effects of adding 0, 15, 25 and 30 percent DDGS to diets for male and female Pekin ducks from 22 to 49 days of age on growth performance and carcass characteristics (Table 3). At slaughter, a subsample of five males and five females were selected from each dietary treatment for evaluation of carcass characteristics. Results of this study showed that adding up to 30 percent DDGS to Pekin duck diets had no effect of live body weight, slaughter yield, carcass weight, breast and leg muscle weight, as well as the weight of skin with subcutaneous fat and abdominal fat weight. Furthermore, there were no differences in pH, color and cholesterol content of breast muscle, but feeding 30 percent DDGS diets increased fat content of breast muscle in males and protein content of breast meat in females. However, final body weight of females fed the 30 percent DDGS was less than males. These results suggest that DDGS can be fed up to 30 percent of the diet for meat ducks.

Table 1. Suggested energy and nutrient requirements for meat type ducks (adapted from Baéza, 2015)

	Starter (day 1-14)	Grower (day 15-35)	Finisher (day 35-49)
AME, kcal/kg	2,800-2,900	2,900-3,000	2,950-3,050
Standardized ileal digestible amino acids %			
Lysine	1.00	0.75	0.65
Methionine	0.37	0.29	0.26
Methionine + cysteine	0.70	0.55	0.49
Tryptophan	0.16	0.13	0.12
Threonine	0.62	0.48	0.44
Arginine	1.05	0.81	0.72
Isoleucine	0.65	0.50	0.45
Valine	0.77	0.59	0.51
Minerals and choline			
Calcium %	0.70	0.65	0.60
Available phosphorus %	0.35	0.32	0.30
Sodium %	0.20	0.16	0.14
Choline, mg/kg	1,800	1,500	1,250

Table 2. Comparison of apparent dry matter, nitrogen and amino acid digestibility (percent) of DDGS, corn, soybean meal and wheat for White Pekin ducks (adapted from Kong and Adeola, 2010)

	DDGS	Corn	Soybean Meal	Wheat
Dry matter	63^{c}	79^{a}	80^{a}	72^{b}
Nitrogen	77^{b}	75^{bc}	88^{a}	79^{b}
Arginine	84^{bc}	79^{cd}	94^{a}	78^{d}
Cystine	73^{a}	54^{b}	81^{a}	72^{a}
Histidine	81^{b}	84^{bc}	92^{a}	83^{b}
Isoleucine	79^{b}	75^{b}	90^{a}	81^{b}
Leucine	88^{a}	85^{ab}	89^{a}	82^{bc}
Lysine	69^{c}	78^{b}	90^{a}	77^{b}
Methionine	85^{b}	86^{b}	92^{a}	85^{b}
Phenylalanine	84^{b}	81^{bc}	90^{a}	84^{b}
Threonine	70^{b}	62^{c}	84^{a}	66^{bc}
Tryptophan	79^{d}	80^{cd}	93^{a}	91^{ab}
Valine	79^{b}	68^{c}	87^{a}	73^{bc}

^{a,b,c,d}ry matterreans within a row with different superscripts differ (P less than 0.01).

Table 3. Effect of dietary DDGS inclusion rate and sex on body weight gain (22 to 49 days of age) and carcass composition of Pekin ducks (adapted from Adamski et al., 2011)

	Control		15% DDGS		25% DDGS		30% DDGS	
	Males	Females	Males	Females	Males	Females	Males	Females
Body weight, g								
Day 1	55	53	53	53	55	54	54	53
Day 21	1,017	976	1,030	1,164	1,118	1,087	1,098	1,008
Day 49	3,036	3,131	3,022	3,117	3,035	2,997	3,028	2,831
Live weight at slaughter, g	3,020	3,090	3,080	3,020	2,950	2,980	2,930	2,890
Carcass weight with neck, g	2,013	1,944	2,057	1,992	1,874	1,948	1,880	1,887
Slaughter yield %	66.6	62.9	66.8	66.0	63.5	65.4	64.2	65.3
Breast muscle, g	224	256	248	234	186	206	194	199
Leg muscle, g	276	258	267	239	267	268	245	249
Total carcass muscle, g	500	514	515	473	453	474	439	448
Skinwithsubcutaneousfat,g	490	587	550	634	457	546	513	561
Abdominal fat, g	21	28	32	39	22	26	24	24

Layer ducks

Similar to meat type ducks, nutrient requirements for laying ducks are not well defined for different types in different countries. However, Baéza (2015) suggested energy and nutrient requirements for laying ducks based on experience and a summary of limited studies (Table 4).

The U.S. Grains Council (USGC) sponsored a study conducted at the I-lan Branch of the Livestock Research Institute in Taiwan. Researchers evaluated the effects of feeding diets containing corn DDGS on the production performance and egg quality of brown Tsaiya duck layers from 14 to 50 weeks of age (Huang et al., 2006). Ducks were randomly assigned to one of four dietary treatments containing 0, 6, 12 or 18 percent DDGS. Diets were isocaloric and isonitrogenous and contained 2,750 kcal/kg ME and 19 percent crude protein. Results from this study showed that adding DDGS at levels up to 18 percent of the diet for laying ducks had no effect on feed intake, feed conversion or quality of the egg shell. When laying ducks were fed the 18 percent DDGS diet, egg production rate increased in the cold season, and egg weight tended to be higher by including 12 percent or 18 percent of DDGS in the diets. Egg yolk color was linearly improved with increasing amounts of DDGS in the diets, which indicates that the xanthophylls (natural pigments) present in DDGS can be well utilized by the laying ducks. Furthermore, when DDGS was added to duck layer diets, fat percentage and linoleic acid content of yolk was increased. These results indicate that DDGS can be effectively added up to 18 percent to layer duck diets to improve the egg yolk characteristics without influencing the egg production and quality.

Geese

Unfortunately, no feeding studies have been published on the effects of feeding DDGS to geese for meat or egg production. Therefore, studies are needed to help this increasing segment of food animal production capture economic and nutritional value from adding DDGS to goose diets.

Summary

Limited published information suggests that DDGS can be used effectively up to 30 percent in meat type duck diets and up to 18 percent in layer duck diets to achieve acceptable performance, meat and egg quality. No studies have been published to determine energy and digestible amino acid content in DDGS for geese and the effects of increasing dietary inclusion rates on performance. However, greater diet inclusion rates are likely possible if energy and nutrient requirements are known for the types of ducks being fed and if accurate AME and digestible amino acid values for DDGS and other feed ingredients are known for ducks. Compared to broilers and layers, ducks and geese are able to utilize high fiber ingredients more effectively, especially when using carbohydrase and phytase enzymes, which suggest that much greater DDGS inclusion rates can be used for ducks and geese. Further research is needed to optimize DDGS use in duck and goose diets.

Table 4. Suggested energy and nutrient requirements for egg laying ducks (adapted from Baéza, 2015)

AME, kcal/kg	2,650
Standardized ileal digestible amino acids %	
Lysine	0.80
Methionine	0.36
Methionine + cysteine	0.64
Tryptophan	0.16
Threonine	0.58
Arginine	0.96
Isoleucine	0.62
Valine	0.72
Minerals and choline	
Calcium %	3.50
Available phosphorus %	0.35
Sodium %	0.20
Choline, mg/kg	1,250

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CHAPTER 21

Reduced-Oil DDGS in Swine Diets

Introduction

CORN DRIED DISTILLERS GRAINS WITH SOLUBLES (DDGS) has become the most popular, economical and widely available alternative feed ingredient for use in U.S. swine diets in all phases of production. Corn DDGS is used primarily as an energy source in swine diets because it contains approximately the same amount of metabolizable energy (ME) as corn. Therefore, DDGS primarily replaces a portion of the corn when added to swine diets, but it also partially replaces some of the soybean meal and inorganic phosphorus. Numerous studies have shown that DDGS can be included up to 30 percent in starter, grower-finisher, and lactation diets, and up to 50 percent in sow gestation diets, with no detrimental effects on performance. In fact, because of the high diet cost saving potential of DDGS, several swine integrators in the U.S. are evaluating the addition of up to 60 percent reduced-oil DDGS in growing-finishing pig diets. However, to successfully achieve acceptable growth performance and carcass characteristics at these high dietary inclusion rates, accurate energy, digestible amino acids and digestible phosphorus values must be determined specifically for the DDGS source being fed. Fortunately, numerous studies have been conducted to develop equations to predict ME and standardized ileal digestible (SID) amino acid content of reduced-oil DDGS sources to help nutritionists manage variability in precision nutrition swine feeding programs.

Determining Accurate Energy and Digestible Nutrient Values

Metabolizable energy

Widespread adoption of distillers corn oil extraction in the U.S. ethanol industry has resulted in a proportional reduction of the quantity of DDGS produced, and an increase in the variability in ME and nutrient content among sources. Crude fat content in DDGS ranges from 4 to 13 percent, neutral detergent fiber (NDF) content ranges from 21 to 34 percent, and crude protein content ranges from 24 to 35 percent among DDGS sources (Kerr et al., 2013). However, due to the high variability in nutrient content among DDGS sources before oil extraction (Stein and Shurson, 2009), there is not a consistent increase in the concentration of other nutrients among sources after oil is extracted.

Nutrient composition of feed ingredients has a major impact on their energy content, because pigs digest and utilize protein, starch, fiber and lipids with different efficiencies (Patience, 2009). As a result, estimates of the ME content of reduced-oil DDGS for swine have been reported to vary from 2,858 kcal/kg (Table 1.) Although these ME estimates vary considerable, they generally indicate that the ME content in corn DDGS is about 93 percent of the ME content relative to corn. However, oil (crude fat) content is a poor single predictor of ME content in DDGS for swine (Table 2). The NRC (2012) reported a mean ME content of 3,845 kcal/kg for DDGS sources containing more than 10 percent oil (high oil), 3,801 kcal/kg for sources with 6 to 9 percent oil (medium oil), and 3,476 kcal/kg for sources with less than 4 percent oil (low oil). However, it is important to note that the published ME values for the medium- and low-oil DDGS were based on only a few published values, and therefore, the accuracy of these values is questionable.

Several factors appear to affect variability in ME content of reduced-oil DDGS among sources. Kim et al. (2013) reported that only about 50 percent of the oil in DDGS is digestible for swine, and Kerr et al. (2013) reported that apparent total tract digestibility (ATTD) of ether extract ranges from 53 to 81 percent among sources. Second, ATTD of fiber in DDGS for swine ranges from 23 to 55 percent (Urriola et al., 2010), which also contributes to variable ME content. Differences in EE and fiber digestibility among DDGS sources appear to be due to differences in the porosity of the fiber-starch-protein matrix in various DDGS sources, which affects fermentability of fiber and effectiveness of carbohydrase enzymes (Jha et al., 2015). Particle size varies among DDGS sources, and Liu et al. (2012) showed that ME content of DDGS is improved by grinding to smaller particle size.

dry matter digestibility of the DDGS sources evaluated by Kerr et al. (2013) was relatively high, ranging from 66.8 to 77.3 percent, but there was no strong association between dry matter digestibility and ME content (Table 3). However, the range in digestibility was rather large (52.7 to 81.2 percent) among sources but not strongly associated with ME content. Eight of DDGS sources had ether extract digestibility values in the 50th percentile, which partially explains why crude fat content is a single poor predictor of ME content. A significant amount of NDF in DDGS is utilized for energy, with apparent total tract digestibility values ranging from 45.8 to 61.5 percent. These results are similar to those reported by Urriola et al. (2010). Digestibility of nitrogen (crude protein) was less variable among DDGS sources, and ranged from 76.9 to 84.8 percent, but was poorly associated with ME content. Excess nitrogen can

Table 1. Summary of published estimates for ME (kcal/kg dry matter) content of DDGS relative to ME content of corn (NRC, 2012)

		ME of DDGS				DDGS relative to corn[1] (%)
Item	n	Average	Least value	Greatest value	SD	
Hastad et al., 2004[2]	2	4,047	3,986	4,108	-	105.3
Hastad et al., 2004[3]	2	3,679	3,476	3,882	-	95.7
Stein et al., 2006	4	3,378	-	-	-	87.9
Pedersen et al., 2007	10	3,897	3,674	4,336	221	101.4
Stein et al., 2009	4	3,750	3,575	3,976	168	97.6
Dahlen et al., 2011	2	2,962	2,959	2,964	-	77.0
Jacela et al., 2011[4, 5]	1	2,858	-	-	-	74.3
Liu et al., 2012	3	3,730	3,583	3,862	140	97.0
Anderson et al., 2012	6	3,790	3,414	4,141	252	98.6
Anderson et al., 2012[5]	1	3,650	-	-	-	94.9
Kerr et al., 2013[5]	15	3,435	3,266	3,696	140	89.3
NRC, 2012, >10 % oil	-	3,845	-	-	-	100.0
NRC, 2012, > 6 and < 9 % oil	-	3,801	-	-	-	98.9
NRC, 2012, < 4 % oil	-	3,476	-	-	-	90.4
Graham et al., 2014a[4, 5]	1	3,365	-	-	-	87.5
Graham et al., 2014b[5]	4	3,744	3,481	3,905	183	97.4
Adeola et al., 2014	1	3,559	-	-	-	92.6

[1] Average ME of DDGS sources as percentage of ME value of corn from NRC (2012)

[2] MEofDDGSdeterminedusingmetabolismstudy.Moisturecontentwasnotreported,andvalueswererepresentedondrymatterbasisassuming89.3percentdrymatter(NRC,2012)

[3] MEofDDGSdeterminedusinggrowthassay.Moisturecontentwasnotreported,andvalueswererepresentedondrymatterbasisassuming89.3percentdrymatter(NRC,2012)

[4] ME was calculated using equation from Noblet and Perez (1993) based on determined DE and analyzed chemical composition

[5] Studies involved reduced-oil (less than 10 percent) DDGS sources

Table 2. Ranking of ME content of DDGS sources with variable crude fat content and other nutrient components for swine (dry matter basis; adapted from Kerr et al., 2013)

DDGS Source	ME, kcal/kg	ME/GE %	Crude fat %	NDF %	Crude protein %	Starch %	Ash %
15	3,696	72.8	10.9	31.6	29.0	3.3	5.4
13	3,604	74.6	5.6	31.6	30.6	3.3	6.1
8	3,603	69.7	13.2	34.0	30.6	1.3	5.3
11	3,553	69.3	11.8	38.9	32.1	1.1	4.9
9	3,550	71.6	9.7	28.8	29.8	2.8	5.0
6	3,513	70.8	9.6	33.0	30.1	3.4	4.9
7	3,423	69.3	10.1	38.2	30.3	2.2	5.0
2	3,400	67.0	11.1	36.5	29.7	3.9	4.3
4	3,362	68.7	8.6	35.7	32.9	0.8	5.1
3	3,360	66.4	10.8	38.6	29.7	1.6	4.6
10	3,327	67.2	10.0	35.9	32.7	1.0	5.3
1	3,302	65.0	11.2	44.0	27.7	1.8	4.4
12	3,286	68.8	4.9	30.5	31.2	3.3	5.8
5	3,277	65.0	11.1	39.7	31.6	0.9	5.0
14	3,266	66.2	7.5	33.9	30.8	2.5	5.7

Table 3. Ranking of ME content of DDGS sources with variable crude fat content and other nutrient components for swine (dry matter basis; adapted from Kerr et al., 2013)

DDGS Source	ME, kcal/kg	ATTD DM %	ATTD Ether extract %	ATTD NDF %	ATTD Nitrogen %	ATTD Carbon %
15	3,696	72.5	81.2	45.8	80.5	74.1
13	3,604	77.3	69.8	57.4	83.4	78.1
8	3,603	71.6	68.5	57.1	81.0	73.0
11	3,553	70.4	65.8	53.3	82.5	72.4
9	3,550	73.8	58.2	55.2	84.8	74.7
6	3,513	74.2	53.3	60.6	82.8	74.3
7	3,423	71.9	52.7	61.5	80.6	73.2
2	3,400	70.5	57.2	57.4	79.7	71.0
4	3,362	73.3	67.1	51.8	77.0	72.3
3	3,360	69.6	54.7	58.2	81.8	70.2
10	3,327	70.4	57.6	57.2	81.8	70.5
1	3,302	66.8	54.8	56.3	76.9	67.9
12	3,286	72.4	65.7	49.8	82.6	73.6
5	3,277	67.4	59.4	54.2	82.1	68.3
14	3,266	67.7	72.7	44.5	78.0	69.0

be utilized as energy, but it is an energetically expensive process. Similarly, carbon digestibility was relatively high and ranged from 67.9 to 78.1 percent, with no clear association with ME content. Therefore, the ME content of DDGS with variable oil content is determined by a combination of digestible energy contributing fractions (NDF, ether extract, and crude protein) and not solely a function of ether extract content or digestibility.

Accurate and precise estimation of ME values for DDGS sources is important for accurate diet formulation and optimizing the nutritional and economic value of DDGS in swine diets. Several studies have been conducted to develop digestible energy (DE) and ME prediction equations based on physical and chemical composition of corn DDGS sources for swine (Stein et al., 2006; Pedersen et al., 2007; Stein et al., 2009; Anderson et al., 2012; Kerr et al., 2013) and to manage variability in ME content among sources. These equations have been cross-validated for swine (Urriola et al., 2014). The most precise (prediction error = 144 kcal/kg) and accurate (bias = 19 kcal/kg) DE equation was:

$$DE = -2{,}161 + (1.39 \times \text{gross energy}) - (20.7 \times NDF) - (49.3 \times EE)$$

The most precise (prediction error = 149 kcal/kg) and accurate (bias = -82 kcal/kg) ME equation uses the DE value obtained from the previous equation as follows:

$$ME = -261 + (1.05 \times DE) - (7.89 \times \text{crude protein}) + (2.47 \times NDF) - (4.99 \times EE)$$

To further evaluate the most precise and accurate DE and ME prediction equations identified by Urriola et al. (2014), Wu et al. (2016a) conducted a growing-finishing experiment to compare the effects of adding 40 percent DDGS from three sources containing 6 percent (LOW), 10 percent (MED) and 14 percent (HIGH) EE, but similar predicted ME (3,258, 3,315 and 3,232 kcal/kg as-fed, respectively), compared with corn-soybean meal (CON) diets, on growth performance, carcass composition and pork fat quality (Table 4). Diets contained similar concentrations of standardized ileal digestible amino acids and standardized total tract digestible phosphorus within each phase. Results from this study showed that pigs fed diets containing 40 percent DDGS are likely to have slightly depressed feed intake, which may be due to the elevated fiber content in DDGS compared with that in maize-soybean meal diets. However, feeding DDGS with variable oil content, but similar predicted ME content, had no effect on overall ADG and carcass characteristics. The lower oil content of the low and med DDGS sources reduced polyunsaturated fatty acid intake of pigs, and resulted in improved pork fat quality by reducing iodine value (IV) of belly fat. Furthermore, these results show that the ME content of DDGS with greater than 6 percent oil content can be accurately and precisely predicted using the best equations from Urriola et al. (2014). However, based on slightly reduced gain:feed for pigs fed the low-oil (6 percent EE) DDGS diet,

Table 4. Effects of dietary DDGS with variable ether extract (EE) content on overall growth performance, carcass characteristics, and belly fat quality of growing-finishing pigs (adapted from Wu et al., 2016a)

		40% DDGS			
Item	CON[1]	LOW[1]	MED[1]	HIGH[1]	SEM[2]
No. Pens	12	12	12	12	
Body weight, kg					
Initial	39.24	39.52	38.95	39.58	0.90
Final	122.7[a]	118.7[b]	118.6[b]	119.4[b]	0.90
Overall ADFI, kg	2.72[a]	2.65[ab]	2.61[b]	2.60[b]	0.03
Overall ADG, kg	0.97[a]	0.92[b]	0.92[b]	0.93[b]	0.01
Overall Gain:Feed	0.368[a]	0.356[b]	0.365[a]	0.367[a]	0.003
Hot carcass weight, kg	90.97[a]	86.69[b]	86.80[b]	87.24[b]	0.88
Carcass yield %	74.2[a]	73.0[b]	72.9[b]	73.0[b]	0.20
Backfat depth[3], mm	20.6	19.9	19.2	19.8	0.5
Loin muscle area[3], cm^2	42.06[a]	39.38[b]	39.09[b]	39.37[b]	0.53
Fat-free lean[3] %	51.9	51.6	51.9	51.6	0.3
Belly fat IV[4]	60.17[a]	70.74[b]	72.03[b]	76.41[c]	0.79

[1] CON=corn-soybeanmealcontroldiet;LOW=low-oilDDGS(5.9percentEE)diet;MED=medium-oilDDGS(9.9percentEE)diet;andHIGH=high-oilDDGS(14.2percentEE)diet

[2] Pooled SEM

[3] Final BW was used as covariate in the statistical analysis.

[4] IV = iodine value

[a,b] Means with different superscripts within a row differ (P less than 0.05)

further refinements in ME prediction equations may be needed to accurately predicting ME content of low-oil (less than 6 percent EE) DDGS sources. As described by Urriola et al. (2014) it is important to note that energy prediction equations from NRC (2012) should not be used because they underestimate the true ME content of reduced-oil DDGS sources.

Net energy

The net energy (NE) system provides a more accurate method of meeting the energy requirements of pigs fed high-fiber diets than the ME system (Noblet et al., 1994). As a result, swine nutritionists in the U.S. are using the NE system to formulate DDGS diets to achieve satisfactory growth performance and carcass composition at high (greater than 30 percent) diet inclusion rates. Unfortunately, a limited number of studies have been conducted to determine the NE (dry matter basis) content of DDGS sources (Table 5).

Using the comparative slaughter method, Gutierrez et al. (2014) determined NE concentrations of a conventional DDGS source (13.0 percent EE) and an uncooked (enzyme-treated prior to fermentation) DDGS source (2.6 percent EE). The conventional DDGS source had less NE content when fed to pigs during the growing phase compared with feeding it during the finishing phase (2,173 vs. 2,697 kcal/kg, respectively). However, the NE content of the uncooked DDGS source was not different between the growing and finishing periods (2,120 and 2,058 kcal/kg). It is unclear why the NE content of the uncooked DDGS source was less compared with the NE content of the conventional DDGS source during the finishing phase, but not during in growing phase. It may be possible that the greater oil content of conventional DDGS resulted in greater fat accretion in the carcass compared with feeding the lower crude fat uncooked DDGS source, which may be more prominent in the finishing phase because finishing pigs deposit much more carcass lipid than growing pigs (Gutierrez et al., 2014). Furthermore, these NE estimates for DDGS sources were lower than the NE value for corn (NRC, 2012), and were also lower than the NRC (2012) NE values (2,669 kcal/kg for DDGS with greater than 10 percent oil and 2,251 kcal/kg for DDGS with less than 4 percent oil). However, it is important to realize that the NE values in NRC (2012) are questionable because they were not directly determined with in vivo experiments, but were calculated using prediction equations developed based on complete feeds.

Kerr et al. (2015a) determined NE content of six corn DDGS sources using the Dual-energy X-ray absorptiometry method (Table 6). Although oil concentrations of these DDGS sources varied from 7.0 to 13.3 percent, NE content was not different among sources (2,012 to 2,253 kcal/kg). The average NE content of these six sources was 2,135 kcal/kg, with the low NE value being 29.4 and 12.3 percent less than the NE content of corn (NRC, 2012) and conventional DDGS (average between grower and finisher periods) determined by Gutierrez et al. (2014), respectively. Results from this study confirmed once again that crude fat content of DDGS is not a good indicator of energy content among DDGS sources. Unfortunately, Kerr et al. (2015) were unable to develop NE prediction equations from this limited number of DDGS sources because of a lack of high variability in chemical composition among the sources evaluated.

In other experiments, Graham et al. (2014b) estimated the NE concentrations of four DDGS sources by calculating and comparing the NE efficiencies of pigs fed DDGS diets with pigs fed a corn-soybean meal control diet and using NRC (2012) published values for NE content of corn and soybean meal. Estimated NE values ranged from 2,122 to 2,893 kcal/kg and appeared to be positively correlated to the EE concentration of DDGS (NE, kcal/kg = 1,501.01 + 115.011 × EE %; adjusted $R^2 = 0.86$). Most recently, Wu et al. (2016) fed 4 DDGS sources with variable crude fat and estimated NE content to growing-finishing pigs and used growth performance responses and the NRC (2012) requirement model to estimate actual NE content of these sources. The NE estimates ranged from 2,182 to 2,915 kcal/kg, with an average of 2,660 kcal/kg dry matter. These estimates are substantially greater than those published in NRC (2012), but similar to those reported by Graham et al. (2014b). Wu et al. (2016c) used the results from Kerr et al. (2015a) and Wu et al. (2016c) to develop a NE prediction equation for DDGS with oil content ranging between 5.8 to 12.2 percent ether extract:

NE (kcal/kg dry matter) = -1130.5 + (0.727 × gross energy) + (23.86 × ether extract) – (10.83 × NDF); ($R^2 = 0.99$; phosphorus less than 0.01).

However, the accuracy of the predicted NE values for RO-DDGS using this equation has not been validated in feeding trials with growing-finishing pigs. Summarizing all of the available published results, the most conservative estimate of

Table 5. Summary of published estimates for NE (kcal/kg dry matter) content of corn DDGS

		NE of DDGS				
Item	n	Average	Least value	Greatest value	SD	DDGS relative to corn[1] (%)
Gutierrez et al., 2014[2]	1	2,435	-	-	-	80.5
Gutierrez et al., 2014[3]	1	2,089	-	-	-	69.1
Graham et al., 2014b	4	2,551	2,122	2,893	318.8	84.3
Kerr et al., 2015a	6	2,135	2,012	2,253	89.2	70.6
Wu et al., 2016c	4	2,660	2,182	2,915	-	87.9
NRC, 2012, > 10 % oil	-	2,384	-	-	-	78.8
NRC, 2012, > 6 and < 9 % oil	-	2,343	-	-	-	77.4
NRC, 2012, < 4 % oil	-	2,009	-	-	-	66.4

[1] Average NE of DDGS sources as percentage of NE value of corn from NRC (2012)

[2] Conventional DDGS source

[3] Uncooked (enzyme-treated prior to fermentation) DDGS source

Table 6. Ranking of NE content of DDGS sources with variable crude fat content and other nutrient components for swine (dry matter basis; adapted from Kerr et al., 2015)

DDGS Source	NE, kcal/kg	ME, kcal/kg	NE/GE %	NE/ME %	Crude fat %	NDF %	Crude protein %	Starch %	Ash %
6	2,381	3,734	44.8	59.3	11.4	31.1	32.2	4.7	5.5
5	2,326	3,893	45.9	60.4	7.0	27.8	29.8	4.4	5.5
1	2,262	3,830	42.6	58.2	13.3	38.3	29.7	2.5	4.8
2	2,249	3,723	43.0	58.9	10.4	38.5	32.0	2.3	4.7
3	2,219	3,874	42.6	55.5	9.1	39.6	31.6	3.8	5.4
4	2,129	3,716	42.3	56.7	8.0	31.0	30.6	4.9	5.6

NE content in reduced-oil DDGS is 2,012 kcal/kg, but using an average NE value of 2,374 kcal/kg dry matter may be appropriate for most DDGS sources.

Digestible amino acids

One of the most significant constraints that affect the dietary inclusion rates of DDGS is the inherent variability in digestible amino acid content among sources. Several studies have been conducted and published that have determined the standardized ileal digestibility (SID) of amino acids in various DDGS sources. However, to use higher dietary inclusion rates of DDGS, nutritionists need methods to dynamically estimate digestible amino acid content of the specific DDGS source(s) they are using in commercial feed formulas. Currently, dietary DDGS inclusion rates are restricted because of concerns on potential reductions in growth performance when feeding high DDGS diets resulting from less digestible and less balanced amino acid profile of DDGS compared with soybean meal, as well as variability among sources.

Olukosi and Adebiyi (2013) summarized amino acid composition data of corn DDGS sources from published studies from 1997 to 2010 (Table 7). Although the majority of these DDGS sources contained greater than 10 percent crude fat, these data are useful in understanding the inherent variability in total amino acid content among DDGS sources. Furthermore, these researchers showed that the correlations between crude protein content and arginine (r = 0.44), isoleucine (r = 0.26), lysine (r = 0.22) and tryptophan (r = 0.33) were low and not significant. This means that crude protein is a poor indicator of the concentrations of these amino acids in corn DDGS and prediction equations were not developed. Although the concentrations of other indispensable amino acids were significantly correlated with crude protein content (r = 0.68, 0.49, 0.73, 0.81, 0.59 and 0.61 for histidine, leucine, methionine, phenylalanine, threonine and valine, respectively), they were generally low and resulted in prediction equations with low R^2 values (0.23 to 0.66). These results confirm that crude protein content is a poor predictor of amino acid content in corn DDGS, and direct measurement of amino acids is required for accurate determinations.

Four studies have been conducted to determine the effects of partial oil extraction from DDGS on standardized ileal digestibility (SID) of amino acids and SID amino acid content (SIDC). Ren et al. (2011) showed that SID of amino acids in low-oil (2.9 to 4.1 percent ether extract) DDGS sources were not different than conventional high-oil (greater than 10 percent ether extract). Li et al. (2015) evaluated different condensed distillers solubles ratios and oil content in DDGS and showed that reduced-oil DDGS had lower SID of amino acids than high-oil DDGS, and a high CDS ratio tended to decrease SID of amino acids in high-oil DDGS, but not in low-oil DDGS. Curry et al. (2014) showed that 2 sources of reduced-oil DDGS (8.4 and 7.9 percent acid hydrolyzed EE; dry matter basis) had decreased SID values for most amino acids relative to conventional DDGS (12.7 percent acid hydrolyzed EE), and that the lower amino acid digestibility in reduced-oil DDGS could not be overcome by adding fat to the diets (Table 8). A study conducted by Gutierrez et al. (2016) also found that apparent ileal digestibility of dietary lysine was decreased when increasing amounts of a reduced-oil DDGS source was added to corn-soybean meal based swine diets. However, addition of 6 percent soybean oil to these diets increased the apparent ileal digestibility of lysine. It may be possible that significant changes occur in the fiber-starch-protein matrix during the oil extraction process, causing greater susceptibility to heat damage during the drying process, which may contribute to the slight reductions in amino acid digestibility, observed in these two studies. Prediction equations have been

Table 7. Variation in indispensable amino acid composition of corn DDGS sources from 1997 to 2010 (adapted from Olukosi and Adebiyi, 2013)

	Average	Minimum	Maximum	SD	CV %
Arginine %	1.22	1.06	1.46	0.098	8.0
Cysteine %	1.73	1.49	1.97	0.057	11.1
Histidine %	0.74	0.65	0.91	0.070	9.4
Isoleucine %	1.07	0.96	1.25	0.072	6.7
Leucine %	3.21	2.89	3.62	0.210	6.6
Lysine %	0.90	0.62	1.11	0.118	13.1
Methionine %	0.52	0.44	0.72	0.063	12.0
Phenyalanine %	1.29	1.09	1.51	0.123	9.6
Threonine %	1.03	0.93	1.16	0.067	6.5
Tryptophan %	0.22	0.16	0.26	0.022	10.3
Valine %	1.42	1.30	1.61	0.095	6.7

Table 8. Total amino acid content, standardized ileal digestibility (SID), and standardized ileal digestible amino acid content (AIDC) of DDGS sources with varying crude fat content for swine (as-fed basis; adapted from Curry et al., 2014).

	11.5% oil DDGS			7.5% oil DDGS			6.9% oil DDGS		
	Total %	SID %	SIDC %	Total %	SID %	SIDC %	Total %	SID %	SIDC %
Dry matter %	90.6	-	-	89.0	-	-	87.5	-	-
AH EE[1] %	11.5	-	-	7.5			6.9		
Crude protein %	25.7	79.8^{a}	20.5	28.0	72.8^{b}	20.4	27.9	73.6^{b}	20.5
Arg	1.22	87.7^{a}	1.07	1.22	81.0^{c}	0.99	1.24	82.5^{bc}	1.02
Cys	0.62	76.0^{a}	0.47	0.62	67.8^{c}	0.42	0.63	68.8^{bc}	0.43
His	0.69	80.9^{a}	0.56	0.75	73.5^{b}	0.55	0.71	74.6^{b}	0.53
Ile	1.03	79.8^{a}	0.82	1.12	72.9^{b}	0.82	1.06	73.1^{bc}	0.77
Leu	2.79	87.7^{a}	2.45	3.17	83.4^{bc}	2.64	3.07	82.2^{c}	2.52
Lys	0.91	67.9^{a}	0.62	0.91	56.4^{c}	0.51	0.88	61.7^{b}	0.54
Met	0.52	88.1^{a}	0.46	0.59	84.8^{bc}	0.50	0.55	83.6^{c}	0.46
Phe	1.25	84.9^{a}	1.06	1.36	80.3^{bc}	1.09	1.35	79.8^{c}	1.08
Thr	0.97	73.4^{a}	0.71	1.02	66.9^{c}	0.68	1.02	68.2^{bc}	0.70
Trp	0.21	83.1^{a}	0.17	0.20	77.8^{c}	0.16	0.20	81.1^{ab}	0.16
Val	1.30	80.5^{a}	1.05	1.43	74.2^{bc}	1.06	1.33	74.6^{bc}	0.99

[a,b,c]Means within rows of similar columns with different superscripts are different (P less than 0.05)

[1]AH EE = acid hydrolyzed ether extract

developed for estimating amino acid digestibility in heat-damaged DDGS (Almeida et al., 2013), but they have not been validated for accuracy or precision.

Recently, Zeng et al. (2017) summarized data sets from 22 peer-reviewed publications and one master's thesis published between 2006 and 2015 (Table 9 and 10). These data are more reflective of the chemical composition and variability among corn reduced-oil DDGS sources than those reported by Olukosi and Adebiyi (2013). These researchers conducted a meta-analysis to develop standardized ileal digestible amino acid prediction equations for reduced-oil DDGS for swine (Table 11). Amino acid and NDF or ADF content of DDGS are good predictors of SID amino acid content of DDGS for growing pigs, and the accuracy and precision of these prediction equations are much improved compared to those from previously published studies. As a result, these equations can be used to accurately estimate the SID amino acid content of a wide range of reduced-oil DDGS sources for swine.

Table 9. Variation in chemical composition of corn DDGS sources fed to swine from 2006 to 2015 (88 percent dry matter basis; adapted from Zeng et al., 2017)

Nutrient	Average	CV %
Crude protein %	27.1	8.7
Crude fiber %	8.2	26.2
NDF %	34.1	13.4
ADF %	11.5	21.2
Ether extract %	8.8	36.3
Ash %	4.1	24.9

Table 10. Variation in total amino acid content and standardized ileal digestibility (SID) and variability (coefficient of variation; CV %) of corn DDGS sources fed to swine from 2006 to 2015 (88 percent dry matter basis; adapted from Zeng et al., 2017)

Indispensible amino acid	Average total %	CV %	SID coefficient %	CV %
Arginine %	1.15	11.8	0.83	6.8
Histidine %	0.74	14.2	0.78	5.5
Isoleucine %	0.99	11.8	0.76	9.2
Leucine %	3.16	13.7	0.85	4.0
Lysine %	0.80	17.9	0.62	13.5
Methionine %	0.54	15.1	0.82	7.0
Phenylalanine %	1.32	12.3	0.82	4.5
Threonine %	1.01	15.5	0.71	7.1
Tryptophan %	0.20	16.3	0.72	12.7
Valine %	1.35	11.1	0.77	5.9

Table 11. Standardized ileal digestible (SID) amino acid content prediction equations for DDGS fed to swine (88 percent dry matter basis; Zeng et al., 2017)

Amino acid, g/kg	Equation	R2
SID Arginine	= -0.26 + (Arg, g/kg × 0.97) – (NDF, g/kg × 0.004)	0.99
SID Histidine	= -0.08 + (His, g/kg × 0.94) – (NDF, g/kg × 0.003)	0.99
SID Isoleucine	= 0.07 + (Ile, g/kg × 0.90) – (NDF, g/kg × 0.005)	0.99
SID Leucine	= 0.30 + (Leu, g/kg × 0.90) – (ADF, g/kg × 0.018)	0.97
SID Lysine	= -1.03 + (Lys, g/kg × 0.88) – (NDF, g/kg × 0.003)	0.98
SID Methionine	= -0.22 + (Met, g/kg × 1.00) – (NDF, g/kg × 0.002)	0.99
SID Methionine + Cysteine	= 0.05 + (Met+Cys, g/kg × 0.92) – (NDF, g/kg × 0.005)	0.99
SID Phenylalanine	= 0.15 + (Phe, g/kg × 0.92) – (NDF, g/kg × 0.004)	0.99
SID Threonine	= 1.30 + (Thr, g/kg × 0.64) – (ADF, g/kg × 0.028)	0.99
SID Tryptophan	= -0.17 + (Trp, g/kg × 0.89)	0.99
SID Valine	= -0.49 + (Val, g/kg × 0.87) – (ADF, g/kg × 0.070)	0.99

Despite the results of initial studies showing that DDGS color (L* and b*) may be useful in estimating digestible amino acid content of DDGS sources for swine and poultry, a recent study conducted by Urriola et al. (2013) showed that color is not an accurate predictor of amino acid digestibility in DDGS. Urriola et al. (2013) determined the standardized ileal digestibility of amino acids in 34 sources of corn DDGS, one source of sorghum DDGS and two sources of wheat DDGS (Figure 1). These results show that amino acid digestibility can vary significantly among DDGS sources, and while an L* value less than 50 is better correlated with digestible lysine content than an L* greater than 50, the R^2 in both comparisons is low (0.48 and 0.03, respectively). Therefore, color should not be used as a predictor of digestible amino acid content in corn DDGS.

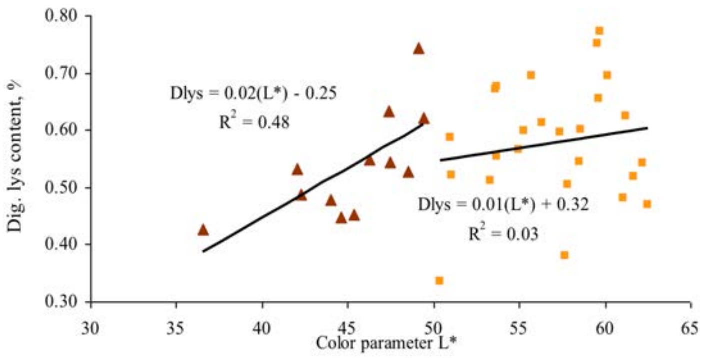

Figure 1. Correlation between lightness of color (L*) and digestible lysine content of 37 sources of DDGS (Urriola et al., 2013)

Researchers at the University of Minnesota have developed methods using optical density and front face fluorescence (Urriola et al., 2013)Lys, Met, Thr and Trp from 34 sources of DDGS to estimate digestibility of amino acids in DDGS. The reduced amino acid digestibility among some sources of DDGS is partly due to heat treatment during the production and drying process. Mild heating of proteins in the presence of reducing sugars forms Schiff's bases or early Maillard products, while more aggressive heating produces advanced Maillard products or melanoidins. A portion of early Maillard products have ring structures, which can be detected using fluorescence. Font face fluoresce is a rapid method that allows quantification of heat damage in DDGS and was calibrated to predict SID of amino acids (Urriola et al., 2013)Lys, Met, Thr, and Trp from 34 sources of DDGS. However, the accuracy of using this method for estimating SID of amino acids among DDGS sources has not been validated.

Studies have also shown that amino acids in DDGS may not only less digestible, but may also be less bioavailable (Fontaine et al., 2007; Pahm et al., 2008). Heat treatment during drying of DDGS can have several effects on the proteins in feed ingredients (Meade et al. 2005). Not only does heat directly degrade lysine, but it also increases the proportion of lysine that is less digestible and less absorbable, or is excreted in urine without utilization after absorption (Rutherfurd, 2015) lysine can undergo Maillard reactions to produce nutritionally unavailable products. The guanidination reaction, the reaction of O-methylisourea with the side chain amino group of lysine that produces homoarginine, has been used to determine the unmodified lysine (reactive lysine). Overall, exposure to heat decreases the proportion of bioavailable lysine that is digestible and utilized for protein deposition, which can lead to reduced growth performance and percentage of carcass lean in pigs (Almeida et al., 2014).

The heat damage to amino acids in DDGS is currently attributed to the Maillard reactions that occur when a mixture of proteins (about 27 percent in DDGS) and sugars or starch (about 2-8 percent in DDGS) are tightly bound during heat treatment (Fontaine et al., 2007). However, lipids (5-12 percent ether extract in DDGS) and products of lipid peroxidation also react with the amino acids in the matrix to produce degradation products that are not bioavailable (Meade et al., 2005). Thermal stress leads to the peroxidation of unsaturated fatty acids (such as linoleic acid in corn oil) which results in the formation of hydroperoxides, aldehydes, ketones and other peroxidation products. Hydroperoxides can oxidize methionine, cystine and tryptophan, while aldehydes and ketones react with lysine and histidine. Previous studies have shown during heat treatment of corn oil when drying DDGS, there is an increase in hydroperoxides and aldehydes, which can be 20 to 25 times greater than found in corn oil from corn grain (Song and Shurson, 2013) growth performance and meat quality. The objective of this study was to determine the lipid peroxidation level in corn DDGS. Therefore, due to the variable oil content among corn DDGS sources, the impact of heat may not only contribute to the formation of Maillard products, but also cause the production of lipid peroxidation products that can reduce the digestibility of lysine and other amino acids.

There are multiple methods that have been developed determine the proportion of bioavailable lysine in feed ingredients including the furosine method (Finot, 2005), the reactive or guanidination method (Rutherfurd, 2015). The guanidination reaction, the reaction of O-methylisourea with the side chain amino group of lysine that produces homoarginine, has been used to determine the unmodified lysine (reactive lysine, and other chemometric methods such as front-face fluorescence (Urriola et al., 2013) Lys, Met, Thr and Trp from 34 sources of DDGS and liquid chromatography-mass spectrometry (LC-MS; Wang et al., 2016). The guanidination and furosine methods are time consuming and expensive. Consequently, these methods have not been further developed for commercial use in estimating amino acid bioavailability in DDGS sources. Front-face fluorescence (FFF) is a rapid analytical method that has promise for use in measuring the portion of bioavailable lysine in DDGS. However, this method has not been validated and only relies on the formation of ring-like structures that fluoresce. A more holistic analytical method may be the use of LC-MS chemometrics that can quantify a multitude of chemical compounds produced during the thermal treatment process. In fact, LC/MS and FFF have been used to determine quality and the consequences of processing milk (Ntakatsane et al., 2011). More research is needed to find practical, fast, accurate and inexpensive methods for estimating bioavailability of amino acids in DDGS for swine and poultry.

Digestible phosphorus

Phosphorus is the third most expensive component of swine diets, and unlike all other grains and grain co-products, DDGS contains a high concentration of total and digestible phosphorus. Therefore, when adding DDGS to swine diets formulated on a digestible phosphorus basis, significant reductions in inorganic supplementation and diet cost can be achieved. In addition, many ethanol plants add phytase during the ethanol and DDGS production process which further improves the phosphorus digestibility of DDGS, but also contributes to variation in digestible phosphorus content among DDGS sources.

Nutritionists are sometimes confused about various ways of expressing the utilization of dietary phosphorus in pigs. Total phosphorus represents all of the phosphorus present in a feed ingredient and includes the indigestible portion of phosphorus known as phytic acid (phytate) in grains and grain co-products. Therefore, if diets are formulated on a total phosphorus basis, overestimation of the digestible phosphorus content may occur because it does not account for the amount that is available for utilization by pigs. Bioavailable phosphorus is the proportion of total phosphorus that is digested, absorbed and available for use in biological functions or stored in the body. Phosphorus bioavailability is usually determined using a slope-ratio assay in digestibility experiments, and theoretically estimates the digestible and post-absorptive utilization of phosphorus at in body tissues. Bioavailablility of phosphorus is also frequently described as available phosphorus. The approach for determining available phosphorus with the slope-ratio assay involves fitting the slope of a linear titration of dietary phosphorus provided by an inorganic phosphorus source and the resulting response (growth rate or bone ash), and comparing it with the linear titrated slope of the same response criteria of the test ingredient. However, this method has the disadvantages of assuming that the bioavailability of the inorganic source is 100 percent, which is not the case, along with differences in estimates based on the response criteria chosen and relatively high cost. Therefore, when using bioavailability estimates for phosphorus, it is important to remember that these estimates are relative to the bioavailability of the reference inorganic source used in the comparison, and that it does not represent true bioavailability. If this is not considered, diets formulated on an available phosphorus basis will overestimate the actual amount of phosphorus being utilized. To overcome these challenges, most recent studies use methodology to estimate apparent total tract digestibility (ATTD) of phosphorus or standardized total tract digestibility (STTD) of P. The difference between ATTD and STTD phosphorus is that STTD corrects for basal endogenous losses of P, resulting in greater accuracy of estimating true digestibility. Therefore, using ATTD phosphorus values will likely underestimate the true digestibility of phosphorus because it does not account for basal endogenous losses. Shen et al. (2002) estimated that basal endogenous losses of phosphorus in corn accounts for about 26 percent of the daily phosphorus requirement for pigs. Therefore, after correcting for endogenous losses, STTD phosphorus values are additive for all feed ingredients and provides the most accurate estimate of the true digestibility of phosphorus in the diet (Gonçalves et al., 2017).

The NRC (2012) list the ATTD and STTD of phosphorus in DDGS containing between 6 to 9 percent oil to be 60 and 65 percent, respectively. Recent studies show that these estimates are low and rather conservative. Almeida and Stein (2010) determined the STTD phosphorus content of DDGS to be 72.9 percent, and the addition of 500 phytase units/kg of diet of a microbial phytase did not improve STTD phosphorus (75.5 percent) unlike the addition of phytase to corn or soybean meal diets. Furthermore, they showed that formulating diets on a STTD phosphorus basis does not reduce pig growth performance, and the use of phytase, DDGS or the combination of both in corn-soybean meal diets reduces phosphorus excretion in growing pigs. In a subsequent study, Almeida and Stein (2012) showed that the addition of 130, 430, 770 or 1,100 FTU/kg of microbial phytase tended to improve STTD of phosphorus 76.9, 82.9, 82.5 and 83.0 percent, respectively. These researchers developed regression equations to predict STTD of phosphorus in DDGS but the R^2 value was only 0.20, and as a result, were not adequate for predicting STTD of phosphorus in DDGS.

Hanson et al. (2011) demonstrated the advantages of formulating DDGS diets on an available phosphorus basis compared with a total phosphorus basis in diets containing 0, 10 or 20 percent DDGS. Results from this study showed that increasing diet inclusion rates of DDGS reduced total dietary phosphorus content and fecal phosphorus concentration, but did not affect phosphorus excretion, retention, or digestibility. Baker et al. (2013) conducted two experiments to compare values of STTD and relative bioavailability of phosphorus (relative to dicalcium phosphate) in DDGS fed to growing pigs. The STTD of phosphorus in dicalcium phosphate and DDGS were 86.1 percent and 58.8 percent, respectively, and the bioavailability of phosphorus in DDGS was 87 percent relative to dicalcium phosphate. However, these researchers concluded that the relative phosphorus bioavailability in DDGS overestimates the true utilization of phosphorus from DDGS, and estimates for STTD of phosphorus cannot be accurately calculated for relative bioavailability phosphorus values in DDGS. Therefore, it is necessary to determine and use STTD values for phosphorus in feed ingredients fed to pigs to achieve optimal phosphorus nutrition.

Rojas et al. (2013) determined STTD of phosphorus in DDGS with (82.8 percent) and without (76.5 percent) microbial phytase added at 870 FTU/kg of diet, and these values were not significantly different. Presumably, the lack of minimal, if any, improvement in STTD phosphorus in these studies resulting from the addition of phytase was due to the relatively low phytate content in the DDGS sources evaluated.

She et al. (2015) determined the STTD of phosphorus in DDGS sources containing 10.3 percent (high-oil), 9.1 percent (medium-oil) and 3.5 percent (low-oil) DDGS sources when 600 FTU/kg of phytase was added to the diets. The STTD of phosphorus in their experiment were 71.2, 70.8 and 71.8 percent for high-, medium-, and low-oil DDGS sources respectively. These data suggest that oil content of DDGS had no effect on STTD of phosphorus in DDGS.

In summary, the greatest accuracy in achieving optimal phosphorus nutrition when feeding DDGS diets to swine is to formulate diets on a STTD phosphorus basis. Results from recent studies have shown that STTD of phosphorus may vary from 59 to 77 percent, but are generally greater than the value of 65 percent reported by NRC (2012). Unfortunately, adequate prediction equations for estimating STTD of phosphorus in DDGS have not been developed for swine. Therefore, use of a conservative estimate of STTD of phosphorus from NRC

(2012) should be used for DDGS from any source in practical diet formulations. The addition of phytase to DDGS diets has minimal effects on improving phosphorus digestibility, which is likely due to the relatively low phytate content in several DDGS sources. Although the relative bioavailability of phosphorus in DDGS has been estimated to be 87 percent relative to dicalcium phosphate, this value overestimates the true utilization of phosphorus from DDGS.

Growth Performance

Numerous studies have been conducted to evaluate the addition of high-oil and reduced-oil DDGS sources at diet inclusion rates up to 60 percent of the diet, using ME or NE formulation methods for nursery and growing finishing pigs. A meta-analysis was conducted to summarized the overall effects of these factors using 26 peer-reviewed references and one thesis published from 2010 to 2017 including: Asmus et al, 2014a; Benz et al., 2011; Coble et al., 2017; Cromwell et al., 2011; Davis et al., 2015; Duttlinger et al., 2012; Graham et al., 2014a,b,c; Hardry matteran, 2013; Jacela et al., 2011; Jha et al., 2013; Jones et al., 2010; Kerr et al., 2015a; Lammers et al., 2015; Lee et al., 2013; Li et al., 2012; McDonnell et al., 2011; Nemechek et al., 2015; Overholt et al., 2016a; Pompeu et al., 2013; Salyer et al., 2013; Seabolt et al., 2010; Tsai et al., 2017; Wang et al., 2012; Wu et al., 2016a; Ying et al., 2013. Table 12 is a summary of the overall growth performance responses from feeding DDGS diets to nursery and growing-finishing pigs (expressed as a percentage compared with feeding control diets) based on data from these 27 studies and representing 106 observations. There was a small, significant (P less than .05) percentage reduction in ADG (-2.4 percent) and gain:feed (-1.2 percent) of pigs fed DDGS diets compared to those fed control diets with no DDGS, and a trend (P less than 0.10) for a slight reduction (-0.7 percent) in ADFI. However, proper interpretation of these results is extremely important. First, these results are based on studies where more than 20 percent DDGS diets were fed and some studies included in this summary fed diets containing up to 60 percent DDGS. Second, although these overall responses were negative, a 2.4 percent change in ADG is equivalent to growing-finishing pigs gaining 0.90 vs. 0.92 kg per day and having gain:feed of 0.45 vs. 0.46. These small differences are very difficult to measure in commercial swine production systems. Furthermore, the feed cost savings commonly achieved by adding DDGS to swine diets, especially at high (greater than 20 percent) diet inclusion rates far exceeds any slight reduction in growth rate that may occur. Third, these slight reductions were generally due to nutritionists often using inaccurate ME, NE, and digestible amino acid values when formulating DDGS diets, especially in the study representing the poorest (minimum) responses. In fact, the majority of the 106 observations of growth performance responses in the studies showed no change in ADG (72 percent of observations), ADFI (63 percent of obsevations), and gain:feed (67 percent of observations) showed no change when feeding DDGS diets compared with control diets (Table 13).

Table 12. Effects of corn DDGS dietary inclusion on growth performance of pigs (summary of 27 studies since 2010)

	DDGS – control (expressed as %)[1]					
	ADG	ADFI	Gain:Feed	Initial BW[2], kg	Final BW, kg	Feeding days
Observations	106	106	106	106	106	106
Studies	27	27	27	27	27	27
Mean	-2.4**	-0.7*	-1.2**	41.5	101.6	66.4
Minimum	-12.3	-12.8	-17.7	6.7	17.5	20.0
Maximum	4.1	18.0	6.5	105.7	134.9	120

**Means differ from 0 (P less than 0.05)

*Means differ from 0 (P less than 0.10)

[1] The inverse of pooled standard errors of observations was used as a weight factor in the analysis

[2] BW = body weight

Table 13. Effects of corn DDGS dietary inclusion on growth performance responses of pigs (summary of 27 studies since 2010)

		Responses to dietary corn DDGS[1]		
	N	Increased	Reduced	Not changed
ADG	106	0	30	76
ADFI	106	10	29	67
Gain:Feed	106	7	28	71

[1] The number of significant and non-significant results

As shown in Table 14, 72 of the 106 total observations in these studies evaluated growth performance responses to pigs fed reduced-oil DDGS. Pigs fed reduced-oil DDGS had slightly greater, but still small, overall reductions in ADG (-2.6 percent) and gain:feed (-1.1 percent) compared to the small reduction in ADG (-1.7 percent) and gain:feed (-1.3 percent) from feeding high-oil (greater than 10 percent crude fat) DDGS sources. These small differences may be due to using inaccurate energy and digestible amino acid values for reduced-oil DDGS sources when formulating experimental diets. Overall, the majority of observations in these 27 studies showed no change in ADG between feeding high-oil (88 percent) or reduced-oil (64 percent), ADFI (56 percent for high-oil, 67 percent for reduced-oil) and gain:feed (62 percent for high-oil, 69 percent for reduced-oil) DDGS (Table 15).

Although the majority of studies (22 out of 27) used the ME system compared with the NE system (Table 16) to formulate diets, it appears that the use of the NE system resulted in a slightly greater, but still small, reduction in ADG (-2.6 percent), ADFI (-1.8 percent), but less reduction in gain:feed (-0.4 percent) compared with using the ME system (-2.3, -0.5, and -1.5 percent, respectively). These small differences are not of great practical consequences and are likely a result of using less well-defined NE values for the DDGS sources fed in these studies. Again, the majority of observations showed no change (Table 17) in ADG (71 percent for ME, 76 percent for NE), ADFI (64 percent for ME, 62 percent for NE), and gain:feed (59 percent for ME, 100 percent for NE).

Table 14. Effects of feeding high-oil (greater than 10 percent) and reduced-oil (less than 10 percent) corn DDGS on growth performance responses of pigs (summary of 27 studies since 2010)[1]

	DDGS – control (expressed as %)					
	ADG	ADFI	Gain:Feed	Initial BW, kg	Final BW, kg	Feeding days
High-oil DDGS						
Observations	34	34	34	34	34	34
Studies	9	9	9	9	9	9
Mean	-1.7**	-0.3	-1.3**	48.6	119.5	75
Minimum	-9.0	-7.9	-7.6	30.3	81.7	43
Maximum	3.2	8.2	3.7	49.7	134.9	96
Reduced-oil DDGS						
Observations	72	72	72	72	72	72
Studies	19	19	19	19	19	19
Mean	-2.6**	-0.8*	-1.1**	9.4	20.2	25
Minimum	-12.3	-12.8	-17.7	6.7	17.5	20
Maximum	4.1	18.0	6.5	105.7	132.9	120

**Means differ from 0 (P less than 0.05)

*Means differ from 0 (P less than 0.10)

[1]The inverse of pooled standard errors of observations was used as a weight factors in the analysis

[2]BW = body weight

Table 15. Comparison of growth performance responses from feeding diets containing high-oil (greater than 10 percent crude fat) and reduced-oil (less than 10 percent crude fat) corn DDGS of pigs (summary of 27 studies since 2010)

		Responses to high-oil corn DDGS[1]		
	N	Increased	Reduced	Not changed
ADG	34	0	4	30
ADFI	34	9	6	19
Gain:Feed	34	1	12	21
		Responses to reduced-oil corn DDGS[1]		
	N	Increased	Reduced	Not changed
ADG	72	0	26	46
ADFI	72	1	23	48
Gain:Feed	72	6	16	50

[1] The number of significant and non-significant results

Table 16. Effects of using the metabolizable energy (ME) vs. net energy (NE) system in formulating corn DDGS diets on growth performance responses of pigs (summary of 27 studies since 2010)[1]

	DDGS – control (expressed as percent)			Initial BW, kg	Final BW, kg	Feeding days
	ADG	ADFI	Gain:Feed			
ME						
Observations	85	85	85	85	85	85
Studies	22	22	22	22	22	22
Means	-2.3**	-0.5	-1.5**	48.6	119.5	75
Minimum	-12.3	-12.8	-17.7	6.7	17.5	134.9
Maximum	4.1	18.0	6.5	100.6	134.9	96
NE						
Observations	21	21	21	21	21	21
Studies	5	5	5	5	5	5
Means	-2.6**	-1.8**	-0.4	9.4	20.2	25
Minimum	-9.0	-7.9	-4.9	29.1	106.2	20
Maximum	3.2	6.9	3.5	105.7	130.0	93.0

**Means differ from 0 (P less than 0.05)

[1] The inverse of pooled standard errors of observations was used as a weight factor in the analysis

Table 17. Effects of using the metabolizable energy (ME) vs. net energy (NE) system in formulating corn DDGS diets on growth performance responses of pigs (summary of 27 studies since 2010)[1]

		Responses to using ME content of corn DDGS[1]		
	N	Increased	Reduced	Not changed
ADG	85	0	25	60
ADFI	85	10	31	54
Gain:Feed	85	7	28	50
		Responses to NE content of corn DDGS[1]		
	N	Increased	Reduced	Not changed
ADG	21	0	5	16
ADFI	21	0	8	13
Gain:Feed	21	0	0	21

[1] The number of significant and non-significant results

Although there were fewer observations for growth performance responses of nursery pigs (n = 19) compared with growing-finishing pigs (n = 87), the relative decrease in ADG and gain:feed when feeding DDGS diets appeared to be greater in nursery pigs (Table 18). However, among these observations, 68 percent of responses represented no change in ADG, 89 percent showed no change in ADFI and 74 percent of observations showed no effect on gain:feed (Table 19). Therefore, it appears that the greater magnitude of performance reductions in nursery pigs fed DDGS diets were a result of the negative responses in one study. Therefore, if nursery diets are formulated with accurate digestible nutrient composition data for DDGS, no change in growth performance compared with feeding control diets will be observed the majority of the time.

Table 18. Effects of feeding corn DDGS to nursery vs. growing-finishing pigs on growth performance responses (summary of 28 studies since 2010)[1]

	Pig age		
	DDGS – control (expressed as %)		
	< 35 kg BW	> 35 kg BW	Standard Error
Observations	19	87	-
Studies	4	24	-
ADG	-6.3**	-2.2**	1.05
ADFI	-1.8	-3.7**	1.52
Gain:Feed	-3.7**	1.4	1.28

**Means differ from 0 (P less than 0.05)

[1] The inverse of pooled standard errors of observations was used as a weight factor in the analysis

Table 19. Effects of feeding corn DDGS to nursery vs. growing-finishing pigs on growth performance responses (summary of 27 studies since 2010)[1]

		Responses of nursery pigs fed DDGS[1]		
	N	Increased	Reduced	Not changed
ADG	19	0	6	13
ADFI	19	0	2	17
Gain:Feed	19	0	5	14
		Responses of grower-finisher pigs fed DDGS[1]		
	N	Increased	Reduced	Not changed
ADG	87	0	24	63
ADFI	87	10	27	50
Gain:Feed	87	7	23	57

[1]The number of significant and non-significant results

In the U.S., diet inclusion rates of corn DDGS in growing-finishing pigs diets typically range from 20 to 30 percent, but because of the substantial feed cost savings often provided by DDGS, several large pork production companies are beginning to add DDGS at levels up to 60 percent of the diet to achieve even greater feed cost savings, even though growth performance may be slightly reduced. Acceptable pork fat quality can be achieved when feeding diets contain greater than 30 percent DDGS in the U.S. by using a recently approved feed additive (Liponate™; Nutriquest, Mason City, Iowa) to prevent carcass fat depots from becoming softer, or by feeding reduced-oil DDGS and withdrawing it from the diet for a few weeks before slaughter. In contrast, many nutritionists in the DDGS export market are often reluctant to use more than 20 percent DDGS in growing-finishing diets because of concerns of reduced growth performance. As a result, significant feed cost savings are not realized by using lower dietary DDGS inclusion rates. However, using the ME and SID amino acid prediction equations to accurately estimate energy and digestible amino acid content of the DDGS source being fed, should be used to achieve no reductions in growth performance when feeding diets containing up to 30 percent DDGS for growing-finishing pigs. This will also require using supplemental synthetic amino acids and fat or oil to meet the requirements of pigs. A summary of growth performance responses at various dietary DDGS inclusion rates is shown in Table 20. Negligible effects of feeding diets containing up to 20 percent on ADG, ADFI and gain:feed have been observed when feeding reduced-oil DDGS to nursery and growing finishing pigs. In fact, the majority of responses for ADG (70 percent), ADFI (68 percent) and gain:feed (62 percent) showed no change when feeding diets containing 25 to 30 percent DDGS. However, of the limited observations (n = 9), about half showed no change in ADG and ADFI, while the other half showed about a 2.4 to 2.8 percent reduction, respectively. However, the magnitude of these negative responses is small (e.g. 0.90 vs. 0.92 kg/day ADG between DDGS and control diets).

There are several reasons that may explain why feeding diets containing high inclusion rates (greater than 30 percent) of DDGS in diets for swine may result in small decreases in growth performance of pigs. First, DDGS has much greater fiber content (35 to 45 percent NDF) compared with corn and soybean meal. Fiber reduces the ME and NE content of swine diets and also can limit feed intake due to gut fill. As a result, pigs in the nursery and early grower stages may not be able to physically consume enough of a high fiber diet to meet their energy requirement. Research to improve fiber utilization and ME and NE content of DDGS diets by supplementing diets with feed enzymes, has become one of the most widely researched topics in recent years (see Chapter 25). Unfortunately, the use of commercially available carbohydrases and proteases in DDGS diets have not provided consistent of substantial improvements in fiber digestibility and energy content for pigs. Secondly, use of accurate ME or NE values for DDGS in diet formulation is essential. Many nuritionists are unaware of the opportunity to use accurate prediction equations to estimate the variable energy (ME) content in DDGS (Urriola et al., 2014) DE, and ME among sources of corn DDGS. Use of ME values derived from these equations will ensure optimum diet formulations to minimize suboptimal feed intake and growth. Furthermore, standardized ileal digestibility of amino acids are affected by the fiber concentration in DDGS (Urriola and Stein, 2010), which has led to conducting a meta-analysis of published data to provide accurate prediction equations to dynamically estimate the SID amino acid values for corn DDGS based on total amino acid and NDF content of DDGS sources (Zeng et al., 2017)g/kg. In fact, some commercial

Table 20. Effects of diet inclusion rate of corn DDGS on growth performance responses of pigs (summary of 25 studies[1] since 2010)

	DDGS - control		Response to dietary corn DDGS		
DDGS inclusion rate	Mean %	N	Increased	Reduced	Not changed
< 12.5%					
ADG	-0.95	13	0	2	11
ADFI	0.15	13	0	2	11
Gain:Feed	-0.60	13	1	1	11
15 to 20%					
ADG	-0.91*	27	0	3	24
ADFI	-0.65	27	6	6	15
Gain:Feed	-0.66	27	3	7	17
25 to 30%					
ADG	-3.20**	47	0	14	33
ADFI	-0.24	47	4	11	32
Gain:Feed	-2.14**	47	1	17	29
> 30%					
ADG	-2.44**	9	0	5	4
ADFI	-2.28**	9	0	4	5
Gain:Feed	-0.18	9	0	3	6

**Means differ from 0 (P less than 0.05)

*Means differ from 0 (P less than 0.10)

[1] Data from Jha et al. (2015) were omitted from the analysis because DDGS diets contained barley (16 percent), extruded full-fat flaxseed and field peas (20 percent). Data from Benz et al. (2011) were omitted from analysis because DDGS diets were supplemented with peroxidized oil, which resulted approximate 20 times greater iodine value in the DDGS diets compared to the control diet

companies (e.g. Nutriquest, Cargill and Evonik) offer services to nutritionists to estimate the SID of amino acids for DDGS. Therefore, the prediction equations described in this chapter, as well as commercially available services should be used by nutritionists to estimate the ME, NE and SID amino acid content among sources of corn DDGS.

Other aspects of DDGS composition that may affect growth performance of pigs when feeding high (greater than 30 percent) dietary inclusion rates to pigs that have been less studied. Corn DDGS contains high concentrations of fiber, and high dietary fiber increases the threonine requirement of pigs (Zhu et al., 2005). Mathai et al. (2016) showed that the threonine requirement, expressed as a ratio to lysine, was increased for pigs consuming diets with soybean hulls and pea fiber compared with pigs consuming a low fiber diet. Depending on fiber composition, endogenous losses of threonine, and the subsequent requirement of threonine is likely increased when feeding diets containing high concentrations of DDGS (Blank et al., 2012). Based on data from Huang et al. (2017) and Saqui-Salces et al. (2017a) and the NRC (2012) model, the estimated threonine endogenous losses (as a percentage of the requirement) from feeding a high DDGS diets is 7.7 percent compared to feeding a corn-soybean meal diet (3.2 percent). As a result, the optimal SID Thr to SID ratio in DDGS diets may be 61 percent compared with 59 percent in corn-soybean meal diets.

In addition to the role of DDGS fiber on endogenous losses of Thr, DDGS also contains a 3.3 times greater concentration of leucine than soybean meal, and the high proportion of leucine relative to isoleucine (1.12×) and valine (1.47×) may result in a deficiency of isoleucin and valine when feeding high (greater than 30 percent) DDGS diets with reduced soybean meal content to pigs. These three branch chain amino acids share the same degradation pathway through the α-keto-acid dehydrogenase complex (BCKDC). This enzyme is inactivated by a kinase, and its activity is modified by the product of catabolism of leucine (Harris et al., 2004). Consequently, excess intake of leucine increases catabolism of isoleucine and valine (Wiltafsky et al., 2010; Gloaguen et al., 2012) Although Htoo et al. (2017) determined the isoleucine and valine requirements of pigs fed excess leucine (greater than 160 of SID Leu:Lys), diets containing DDGS have different proportions of leucine to isoleucine and valine, and the validity of using these branch chain amino acid ratios when formulating DDGS diets has not been evaluated in large commercial swine production systems. The effect of excess dietary leucine is primarily a reduction in feed intake. Excess leucine content in DDGS, and subsequent catabolism of isoleucine and valine can be mitigated by allowing crude protein from soybean meal to meet the amino acid requirement, and avoiding the use of high amounts of synthetic lysine and other amino acids (less than 0.15% Lys HCl; Stein and Shurson, 2009). However, the current relatively low price of synthetic amino acids and DDGS supports reducing the use of soybean meal and increasing the use of synthetic amino acids in swine diets containing greater than 30% DDGS. Furthermore, the effects of excess dietary leucine on catabolism of isoleucine and valine may also be reduced by adding synthetic isoleucine to the diet to achieve adequate amino acid balance. Studies are underway to evaluate branch chain amino acid balance in diets containing greater than 30% DDGS for nursery and growing-finishing pigs.

Feeder Design and Feeding Management

There are a variety of commercial feeder designs used in commercial swine operations that have various advantages and disadvantages. Bergstrom et al. (2012) evaluated using conventional dry feeders compared with wet-dry feeders and various feeder adjustment openings on growth performance and carcass characteristics of growing pigs. These researchers observed that pigs fed using the wet-dry feeders had greater ADG, ADFI, hot carcass weight and carcass backfat thickness. They also observed that the wet-dry feeder was more sensitive to differences in feeders adjustment compared to the conventional dry feeders. Results from this study led to a subsequent study, where Bergstrom et al. (2014) evaluated pig growth performance and carcass characteristics of growing finishing pigs fed diets containing 20 or 60 percent DDGS using wet-dry or conventional dry feeders (Table 21). A total of 1,080 pigs were used in this study, which was conducted on a commercial farm. Pigs were placed in 40 pens 927 pigs/pen) containing either wet-dry or conventional dry feeders. Diets were formulated on a ME basis using 3,420 kcal/kg ME for DDGS containing greater than 10 percent oil. Standardized ileal digestibility values from Stein et al. (2006) were used for DDGS when formulating the diets. All other ME and SID amino acid values for other ingredients were obtained from NRC (1998). Growth rate, ADFI and final body weight were greater for pigs fed using the wet-dry feeders compared with those fed using the conventional dry feeders, but gain:feed was greater for pigs fed using the conventional dry feeders. As a result, pigs fed using wet-dry feeders had heavier hot carcass weight, greater carcass backfat depth, less carcass fat free lean and lower jowl fat iodine value than pigs fed with the conventional dry feeders. Feeding the 60 percent DDGS slightly reduced ADG, gain:feed,

Table 21. Effects of dietary DDGS inclusion level and feeder design on growth performance and carcass characteristics of growing-finishing pigs (adapted from Bergstrom et al. 2014)

	Feeder Design			
	Wet-dry		Conventional dry	
	20% DDGS	60% DDGS	20% DDGS	60% DDGS
Growth performance, d 0 to 99				
ADG[1,2], kg	0.95	0.92	0.88	0.86
ADFI[1], kg	2.59	2.59	2.28	2.31
Gain:Feed[1,2]	0.367	0.355	0.384	0.382
BW[1], kg	129.2	126.9	122.6	121.3
Carcass characteristics				
Hot carcass weight[1,2], kg	96.6	93.5	90.9	89.8
Carcass yield %	74.9	75.1	74.9	75.2
Backfat depth[1,2], mm	19.0	18.1	16.7	16.2
Loin muscle depth, cm	5.96	5.89	6.10	5.99
Fat-free lean index[1,2] %	49.5	50.0	50.6	50.8
Jowl fat iodine value[1,2]	72.1	80.4	73.5	81.9

[1] Feeder design effect (P less than 0.05)

[2] Diet DDGS inclusion rate effect (P less than 0.05)

and tended to reduce final body weight compared with feeding the 20 percent DDGS diets. Feeding 60 percent DDGS diets resulted in lower hot carcass weight, backfat depth, but greater carcass fat free lean and jowl fat iodine value, but had no effect on carcass yield. These results show that feeder design can have significant effects on growth performance and carcass composition of pigs fed DDGS diets, and that extremely high diet inclusion rates (60 percent) of DDGS may reduce ADG and hot carcass weight, but improve gain:feed and percentage of carcass lean compared with feeding diets containing 20 percent DDGS to growing finishing pigs.

Weber et al. (2015) conducted a study to evaluate growth performance of pigs fed 30 or 60 percent DDGS diets using different feeder space allowances (Table 22). Diets were formulated to be isocaloric by adding varying amounts of choice white grease, and metabolizable energy content of the DDGS source used was estimated using the equation from Noblet and Perez (1993). A 5-phase late-nursery and growing-finishing feeding program was used, and dietary DDGS inclusion rates were 27.5, 30.0, 32.5, 32.5 and 26.3 percent in phase 3, 4, 5, 6 and 7, respectively. Dietary inclusion rates of DDGS for the 60 percent DDGS treatment were 30.0, 59.9, 59.9, 59.9 and 30.0 percent in phase 3, 4, 5, 6 and 7, respectively. There were no interactions between feeder space and DDGS inclusion rate, indicating that feeder space does not affect growth performance and carcass characteristics of pigs fed with 30 percent or 60 percent DDGS diets during the growing-finishing period. Furthermore, there were no differences in final body weight, ADG, ADFI and gain:feed of pigs fed the 30 percent or 60 percent DDGS diets. However, pigs fed the 30 percent DDGS diets had slightly heavier hot carcass weight and greater carcass yield and loin depth at slaughter compared with pigs fed the 60 percent DDGS diets. The results from this study suggest that feeder space allowances provided during the growing-finishing phase had no effect on growth performance or carcass characteristics of pigs fed 30 or 60 percent DDGS diets, but feeding the 60 percent DDGS diets slightly reduced carcass weight, yield and loin depth compared with pigs fed 30 percent DDGS diets.

Table 22. Overall growth performance and carcass characteristics of growing-finish pigs using different feeder space allowances and diet inclusion rates of DDGS during phases 4, 5, and 6 (adapted from Weber et al. 2015)

	Feeder space, cm/pig			Diet[1]	
	4.1	4.9	5.7	30 % DDGS	60 % DDGS
No. pigs/pen	31	31	31	31	31
Body weight, kg					
Day 0	29.9	29.8	29.8	30.3[a]	29.3[b]
Market	121.5	122.2	122.9	122.4	121.9
CV %					
Day 61	18.3	17.9	17.2	18.0	17.6
Day 152	11.1	11.0	9.8	10.9	10.5
ADG, kg	0.91	0.91	0.92	0.91	0.92
ADG carcass, kg	0.69	0.70	0.71	0.71	0.69
ADFI, kg	2.06	2.04	2.04	2.07	2.03
Gain:Feed[2]	0.44	0.45	0.45	0.44	0.45
Gain:Feed[3]	0.34	0.34	0.35	0.34	0.34
Days to market	155.0	156.2	155.8	156.1	155.3
Carcass characteristics					
No. pens	10	10	10	15	15
HCW, kg	92.7	93.4	93.8	93.9[a]	92.7[b]
Yield %	75.2	75.7	76.1	76.1[a]	75.2[b]
Backfat depth, mm	12.8	12.7	12.8	12.6	12.9
Loin depth, mm	63.6	64.4	63.7	64.9[a]	62.9[b]

[a,b] Means within a row and main effect without a common superscript are different (P less than 0.05)

[1] Diet inclusion rate of DDGS during phases 4, 5 and 6

[2] Gain:Feed calculated using live ADG

[3] Gain:Feed calculated using carcass ADG

Myers et al. (2013) fed meal or pelleted diets containing 25 to 45 percent DDGS and 15 to 30 percent bakery meal to evaluate diet form on growth performance and carcass characteristics of growing finishing pigs (n = 1,290), in a five-phase feeding program using conventional dry or wet-dry feeders (Table 23). There was no diet form × feeder design interaction for ADG, but pigs fed pelleted diets had greater ADG than those fed meal diets. Pigs fed using the wet-dry feeders had greater ADG compared with those fed using conventional dry feeders. Pigs fed meal diets using dry feeders had reduced ADFI compared with pigs fed pelleted diets, but ADFI was not different between the two diet forms when fed using the wet-dry feeders. gain:feed was similar for pigs fed meal or pelleted diets using wet-dry feeders, but was reduced for pigs fed the pelleted diets using the dry feeder compared with pigs fed meal diets. There were no diet form × feeder design interactions, or differences between diet forms for any carcass characteristics, but pigs fed using the wet-dry feeder more backfat and lower percentage of carcass fat-free lean than pigs fed using dry feeders.

At certain times, fluctuations in DDGS price and availability may cause it to be used in swine diets intermittently during the growing-finishing phase to capture the greatest economic advantages. Furthermore, commercial feed mills may use multiple sources of DDGS with variable nutrient content and digestibility, which may influence growth performance and carcass composition if dynamic adjustments are not made in energy and amino acid content and digestibility when diets are formulated. Hilbrands et al. (2013) conducted two experiments to determine the effects on growth performance and carcass composition resulting from alternating diets with and without DDGS during the growing finishing phase. In the first experiment, pigs were fed using a three-phase feeding program using corn-soybean meal control diets, or 20 percent or 40 percent DDGS diets continuously or alternating every two weeks between control and 20 percent DDGS diets or control and 40 percent DDGS diets. As shown in Table 24, there were no differences in growth performance or carcass traits of pigs fed 20 percent DDGS diets continuously or fed 20 percent DDGS and control diets alternating every two weeks. However, when diets were alternated every two weeks between the 40 percent DDGS and control diets, hot carcass weight was reduced compared with all other dietary treatments.

In the second experiment conducted by Hilbrands et al. (2013), two sources of DDGS were obtained that had low or high SID amino acid digestibility. Metabolizable energy content of these sources were derived from ME prediction equations from Pedersen et al. (2007).The SID amino acid values from these sources were derived from the IDEA assay

Table 23. Effect of diet form and feeder design on growth performance and carcass composition in growing-finishing pigs fed DDGS diets (adapted from Myers et al., 2013)

	Conventional dry		Wet-Dry	
	Meal	Pellet	Meal	Pellet
Growth performance, day 0 to 91				
ADG^{1,2}, kg	0.84	0.85	0.89	0.91
ADFI^{1,2}, kg	2.29^{a}	2.45^{b}	2.50^{b}	2.51^{b}
Gain:Feed^{1}	0.369^{a}	0.349^{c}	0.357^{bc}	0.361^{ab}
Body weight^{2}, kg	123.1	124.0	127.2	128.5
Pellet quality				
PDI	-	74.0	-	74.0
Fines %	-	36.6	-	36.6
Carcass characteristics				
Hot carcass weight, kg	91.7	92.7	94.1	93.8
Yield %	75.6	75.3	75.6	76.0
Backfat depth^{2}, mm	17.3	17.2	18.8	18.3
Loin depth, cm	6.19	6.05	5.97	5.93
Carcass fat-free lean index^{2} %	50.4	50.4	49.7	49.9

^{a,b}Means within a row without a common superscript are different (P less than 0.05)

^{1}Diet form effect (P less than 0.07)

^{2}Feeder design effect (P less than 0.01)

Table 24. Effects of dietary inclusion and removal of DDGS on growth performance and carcass composition of growing-finishing pigs (adapted from Hilbrands et al., 2013).

	Control diets fed continously	20% DDGS diets fed continously	Alternate between 20% DDGS and control diets	Alternate between 40% DDGS and control diets
Initial body weight, kg	51.3	51.3	51.3	51.4
Final body weight, kg	112.3^{xy}	112.2^{xy}	113.0^{x}	110.6^{y}
ADG, kg	0.87	0.87	0.88	0.85
ADFI, kg	2.70^{xy}	2.75^{x}	2.71^{xy}	2.63^{y}
Gain:Feed	0.323^{ab}	0.317^{a}	0.325^{b}	0.322^{ab}
Hot carcass weight, kg	83.8^{a}	83.6^{a}	84.3^{a}	81.1^{b}
Carcass yield %	74.8	74.6	74.6	73.8
10th rib backfat depth, mm	19.3	20.1	20.4	19.8
Loin muscle area, cm^2	48.8	48.3	48.2	47.6
Carcass lean %	54.4	54.0	53.8	54.2

^{a,b}Means within a row without a common superscript differ (P less than 0.05)

^{x,y}Means within a row without a common superscript differ (P less than 0.10)

(Novus International, St. Louis, MO), and SID amino acid values were obtained from NRC (1994). Values for ME and SID amino acids for corn and soybean meal were obtained from NRC (1998). All diets (corn-soybean meal control (CON), 40 percent DDGS with low digestible amino acids (LD) and 40 percent DDGS with high digestible amino acids (HD) were formulated on a SID amino acid basis and were fed in four phases. Six dietary treatments consisting of 1) CON diets fed continously, 2) LD diets fed continuously, 3) HD diets fed continuously, 4) LD and CON diets alternated by phase, 5) HD and LD diets alternated by phase, and 6) HD and LD diets alternated by phase (Table 25). Pigs fed LD and HD-LD had reduced ADG and lower final body weight compared with CON, and feeding LD resulted in lower ADFI than LD-CON and HD-CON, but gain:feed was not affected by dietary treatment. These results indicate that the SID amino acid content was likely overestimated by the IDEA assay when formulating diets. Pigs fed LD and HD-LD had lower hot carcass weight, yield and loin muscle area than the other dietary treatments. However, periodic inclusion and removal of 40 percent DDGS from diets did not adversely affect overall growth performance regardless of amino acid digestibility of the DDGS source fed. Furthermore, there were no differences in the percentage carcass lean among dietary treatments. Therefore, the results of these two experiments indicate that that alternating between corn-soybean meal and DDGS diets every two weeks does not have meaningful detrimental effects on growth performance or carcass composition.

Carcass Composition

Several studies (n = 20) have been published since 2010 to evaluate the effects of feeding corn DDGS diets on carcass composition of growing-finishing pigs, and overall responses for carcass yiled and percentage carcass lean are summarized in Table 26 and 27 (Asmus et al., 2014; Coble et al., 2017; Cromwell et al., 2011; Davis et al., 2015; Duttlinger et al., 2012; Graham et al., 2014a,b,c; Hardry matteran, 2013; Jacela et al., 2011; Jha et al., 2013; Lee et al., 2013; McDonnell et al., 2011; Nemechek et al., 2015; Overholt et al., 2016; Pompeu et al., 2013; Salyer et al., 2013; Wang et al., 2012; Wu et al., 2016c; Ying et al., 2013). One of the most consistent effects of feeding DDGS diets is a slight reduction in carcass yield. The relatively high fiber content in DDGS increases the weight of the gastrointestinal tract resulting in lower carcass:live weight. From this meta-analysis, for every percentage unit increase of DDGS inclusion in growing-finishing pig diets, carcass yield was decreased by 0.022 percent (relative percentage). This effect appears to be related to DDGS oil content where feeding high-oil (greater than 10 percent) DDGS reduced carcass yield, but feeding reduced-oil DDGS diets resulted in no significant change in yield (Table 27). Use of either the NE or ME system in formulating DDGS diets resulted in similar reduction in carcass yield. However, the percentage of carcass fat-free lean is not affected by feeding diets containing high or reduced-oil DDGS or use of the ME versus NE systems.

Table 25. Effects of feeding diets containing 40 percent DDGS with low (LD) or high (HD) standardized ileal digestible amino acids continuously or alternated every two weeks with control (CON) diets on growth performance and carcass composition of growing-finishing pigs (adapted from Hilbrands et al., 2013)

	CON	LD-CON	HD-CON	LD	HD	HD-LD
Initial body weight, kg	33.2	33.2	33.2	33.2	33.2	33.2
Final body weight, kg	121.5^{ab}	121.6^{ab}	123.0^{a}	115.9^{c}	118.3^{bc}	117.8^{c}
ADG, kg	0.92^{ab}	0.92^{ab}	0.93^{a}	0.86^{c}	0.89^{bc}	0.88^{c}
ADFI, kg	2.70^{ab}	2.72^{a}	2.78^{a}	2.57^{b}	2.73^{ab}	2.68^{ab}
Gain:Feed	0.34	0.34	0.34	0.34	0.33	0.33
Lean gain/day, kg	0.395^{ab}	0.396^{ab}	0.405^{a}	0.362^{d}	0.383^{bc}	0.367^{cd}
Lean gain efficiency	0.15	0.15	0.15	0.14	0.14	0.14
Hot carcass weight, kg	93.3^{a}	92.3^{ab}	94.4^{a}	87.2^{c}	89.4^{bc}	88.5^{c}
Carcass yield %	76.2^{a}	75.8^{ab}	76.0^{ab}	74.7^{c}	75.1^{bc}	74.6^{c}
10th rib backfat depth, mm	21.3^{a}	19.9^{ab}	20.4^{ab}	18.9^{ab}	18.1^{b}	19.8^{ab}
Loin muscle area, cm^2	44.7^{a}	44.7^{a}	45.3^{a}	40.4^{b}	42.7^{ab}	40.6^{b}
Carcass lean %	51.8	52.1	52.1	51.3	52.3	50.8

^{a,b,c,d}Means within a row without a common superscript differ (P less than 0.05)

Table 26. Effects of feeding corn DDGS diets on carcass yield and percentage of fat-free lean of growing-finishing pigs (summary of 20 studies[1] since 2010)

Item	DDGS – control (absolute differences %)		Initial BW, kg	Final BW, kg	Feeding days
	Yield	Fat-free lean			
Observations	75	55	75	75	75
Studies	20	16	20	20	20
Mean	-0.87**	0.05	46.7	120.3	76.5
Minimum	-2.1	-1.6	23.4	86.9	20
Maximum	0.7	1.6	105.7	1.4.9	120

**Means differ from 0 (P less than 0.05)

[1] The inverse of pooled standard errors of observations was used as a weight factor in the analysis

Table 27. Effects of oil content of corn DDGS, and formulating diets on a ME vs. NE system, on carcass yield and percentage carcass fat-free lean of pigs (summary of 20 studies[1] since 2010)

	DDGS oil content		SE	Energy system		SE	P value	
	> 10%	< 10%		ME	NE		Oil content	Energy system
Observations	30	45		60	15			
Studies	8	13		16	4			
Yield	-0.79**	-0.42	0.17	-0.49**	-0.72**	0.16	0.034	0.139
Fat-free lean	0.20	-0.16	0.23	0.24	-0.18	0.14	0.220	<0.01

**Means differ from 0 (P less than 0.05)

*Means differ from 0 (P less than 0.10)

[1] The least squares means are reported. The inverse of pooled standard errors of observations was used as a weight factor in the analysis.

[2] Every percentage unit increase of DDGS inclusion in growing-finishing pig diets resulted in a 0.022 percent decrease (relative percentage) in the carcass yield

Pork fat quality

It has been well documented that feeding corn-soybean meal diets containing increasing dietary levels of DDGS to growing-finishing pigs results in reduced pork fat firmness (Stein and Shurson, 2009; Xu et al., 2010a,b; Benz et al., 2010; Graham et al., 2014a,b; Davis et al., 2015). Pork fat firmness has been commonly measured using iodine value (IV), which is the ratio of unsaturated to saturated fatty acid content in jowl, backfat and belly fat. Several feeding management strategies have been developed, and can be effective in managing fat quality in pork carcasses. These strategies include gradually reducing dietary DDGS level before harvest (Harris et al., 2018), withdrawal of DDGS from the diet for more than three weeks before harvest (Jacela et al., 2009; Xu et al., 2010b; Hilbrands et al., 2013), feeding reduced-oil DDGS (Dahlen et al., 2011; Wu et al., 2016a), and formulating diets using carcass fat IV prediction equations (Wu et al. 2016b).

Numerous regression equations have been developed to predict IV in jowl, backfat, or belly fat based on IV product (IVP) of diets (Madsen et al., 1992; Boyd et al., 1997; Bergstrom et al., 2010; Estrada Restepo, 2013), linoleic acid (C18:2) intake (Averette Gatlin et al., 2002; Benz et al., 2011; Kellner, 2014) and percentage of DDGS in the diet (Cromwell et al., 2011; Estrada Restrepo, 2011). Most recently, Paulk et al. (2015) developed IV prediction equations based on dietary essential fatty acid content, days fed initial and final diets, net energy content of final diet and carcass backfat depth.

Wu et al. (2016) compared the precision and accuracy of predicting backfat IV using these equations and found that the Paulk et al. (2015) equation resulted in the best prediction with the least error and bias (Table 28). Overall, these results showed that reduced oil content of DDGS generally reduced the negative impact of feeding DDGS diets on pork fat quality by reducing the IV of carcass fat depots. However, the magnitude of this improvement was not proportional to the amount of dietary lipid intake and may be affected by differences in the digestibility of oil in DDGS. It is important to remember that fatty acid composition varies among carcass fat depots. Jowl fat has a greater IV than backfat and belly fat, but backfat appears to be the most sensitive to changes in dietary lipid content than jowl fat and belly fat. Use of published carcass fat IV prediction equations resulted in variable precision and accuracy in estimating IV of carcass fat depots. It appears that adding additional factors such as dietary energy content, growth performance and carcass composition measures, as indicated in the Paulk et al. (2015) equations, results in improved carcass fat IV predictions than using those based only on characteristics and quantity of dietary lipids. Using the percentage of DDGS in diets as a predictor of carcass fat depot IV results in the poorest prediction. However, the magnitude of the prediction error and bias of these equations needs to be reduced to achieve more predictable carcass fat IV responses when feeding DDGS diets to growing-finishing pigs.

Table 28. Comparison of prediction equations for estimating iodine value (IV) of carcass backfat, jowl fat, belly fat and the average IV of the three carcass fat depots (adapted from Wu et al., 2016)

Fat depot	Equation	R^2	Prediction error[1]	Bias[2]	Reference
Backfat					
	47.1 + 0.14 × IVP[3] intake/day	0.86	6.43	-4.95	Madsen et al., 1992
	52.4 + 0.315 × diet IVP	-	4.60	-2.15	Boyd et al., 1997
	51.946 + 0.2715 × diet IVP	0.16	6.45	-5.05	Benz et al., 2011
	35.458 + 14.324 × diet C18:2 %	0.73	8.36	-1.08	Benz et al., 2011
	64.5 + 0.432 ×DDGS in diet %	0.92	8.26	7.10	Cromwell et al., 2011
	60.13 + 0.27 × diets IVP	0.81	5.04	3.05	Estrada Restrepo, 2013
	70.06 + 0.29 × DDGS in diet %	0.81	9.19	8.00	Estrada Restrepo, 2013
	84.83 + (6.87 × IEFA) – (3.90 × FEFA) – (0.12 × Id) – (1.30 × Fd) – (0.11 × IEFA × Fd) + (0.048 × FEFA × Id) + (0.12 × FEFA × Fd) – (0.006 × FNE) + (0.0005 × FNE × Fd) – (0.26 × BF)	0.95	4.01	-0.84	Paulk et al., 2015[4]
Jowl fat					
	56.479 + 0.247 × diet IVP	0.32	4.92	-3.69	Benz et al., 2011
	47.469 + 10.111 × diet C18:2 %	0.90	5.57	-1.37	Benz et al., 2011
	64.54 + 0.27 × diet IVP	0.81	6.55	5.66	Estrada Restrepo, 2013
	72.99 + 0.24 × DDGS in diet %	0.81	8.33	7.38	Estrada Restrepo, 2013
	85.50 + (1.08 × IEFA) + (0.87 × FEFA) – (0.014 × Id) – (0.05 × Fd) + (0.038 × IEFA × Id) + (0.054 × FEFA × Fd) – (0.0.0066 × INE) + (0.071 × IBW) – (2.19 × ADFI) – (0.29 × BF)	0.93	4.73	-3.37	Paulk et al., 2015[4]
Belly fat					
	58.32 + 0.25 × diet IVP	0.74	3.43	1.41	Estrada Restrepo, 2013
	67.35 + 0.26 × DDGS in diet %	0.75	6.66	5.53	Estrada Restrepo, 2013
	106.16 + (6.21 × IEFA) – (1.50 × Fd) – (0.11 × IEFA × Fd) – (0.012 × INE) + (0.00069 × INE × Fd) – (0.18 × HCW) – (0.25 × BF)	0.94	3.27	1.73	Paulk et al., 2015[4]
Average of three depots					
	58.103 + 0.2149 × diet IVP	0.93	3.93	-2.23	Kellner, 2014
	58.566 + 0.1393 × C18:2 intake/day, g	0.94	6.17	-4.90	Kellner, 2014

[1] Prediction error (smaller value indicates greater precision of the equation)

[2] Prediction bias (smaller absolute value indicates greater accuracy of the equation; negative value indicates underestimation and positive values indicate overestimation)

[3] IVP = iodine value product = dietary IV × percent dietary lipids × 0.10 (Madsen et al., 1992)

[4] Abbreviations in equations are: I = initial diet, F = final diet, d = days diet is fed, EFA = essential fatty acids (C18:2 and C18:3%), NE = net energy (kcal/kg), BW = body weight (kg), ADFI = average daily feed intake (kg), HCW = hot carcass weight (kg), BF = backfat depth (mm)

Pork lean quality

Several studies have been conducted to evaluate pork lean quality of pigs fed DDGS diets. Leick et al. (2010) fed diets containing 0, 15, 30, 45 and 60 percent DDGS with and without 5 mg/kg ractopamine to growing finishing pigs to evaluate meat quality. Increasing dietary levels of DDGS had no effect on loin pH, subjective and objective color, marbling or fat content, but decreased subjective marbling score, firmness, and increased drip loss. Furthermore, increasing dietary DDGS content decreased belly weight, length, thickness, firmness and L* and increased belly cook loss. Belly and jowl fat IV were increased, resulting from a decrease in monounsaturated:polyunsaturated fatty acid content. Loin TBARS was not affected at 0, 7 or 14 days of storage, but on day 21, TBARS of loins from pigs fed 30, 45 and 60 percent DDGS was increased compared to loins from pigs fed zero and 15 percent DDGS diets. These results suggest that feeding diets containing up to 60 percent DDGS to growing-finishing pigs has minimal effects on loin quality, but decreases belly quality, bacon processing characteristics and fat stability.

McClelland et al. (2012) fed growing-finishing pigs diets containing 0, 15, 30 or 45 percent DDGS diets. Results showed that increasing dietary levels of DDGS increased the concentrations of polyunsaturated fatty acids in carcass fat, which subsequently increased carcass fat IV and reduced belly firmness, but had no effect on slicing yield of cured bellies, quality of fresh bacon slices or eating quality of bacon, sausage or loin chops.

Wang et al. (2012) fed diets containing 0, 15 or 30 percent DDGS, supplemented with 10 or 210 IU/kg, to growing-finishing pigs and reported that feeding DDGS decreased the proportion of saturated fatty acids, and increased the proportion of unsaturated and polyunsaturated fatty acids in adipose and muscle. Increasing the dietary vitamin E content increased the concentration of α-tocopherol in adipose and muscle tissues, and reduced the concentration of total volatile basic nitrogen in vacuum-package fresh loins, which was increased by feeding increasing dietary levels of DDGS. The addition of DDGS to the diet resulted in a increase in TBARS of pork loins on day 13 of storage, but loins from pigs feed DDGS diets with 210 IU/kg vitamin E had significantly reduced TBARS in loins on day 4, 7, 10 and 13 of storage. These data suggest that although feeding diets containing DDGS have some adverse effects on storage shelf life of fresh pork loins, supplementing diets with 210 IU/kg of vitamin partially prevented these effects.

Ying et al. (2013) fed 0 or 30 percent DDGS diets in phase 1, 2, and 3, and 0 or a 20 percent DDGS diet during phase 4, with 0, 50, or 100 mg/kg L-carnitine to growing-finishing pigs to determine the effects on growth performance, carcass traits, and loin and fat quality. There were no DDGS × L-carnitine interactions for any carcass traits, but pigs fed increasing diet concentrations of L-carnitine had greater hot carcass weight, carcass yield, and backfat depth. Feeding L-carnitine increased loin purge loss while feeding DDGS tended to reduce loin marbling scores. Loin chops from pigs fed 50 mg/kg L-carnitine and DDGS had reduced shear force values compared with pigs fed diets containing 0 or 100 mg/kg L-carnitine. Increasing L-carnitine in DDGS diest resulted in increased fresh loin color scores. The concentrations of C18:2n-6 and C20:20 in jowl fat were reduced by feeding increasing levels of L-carnitine in DDGS diets, but not in diets containing no DDGS. These results suggest that feeding DDGS diets containing 50 mg/kg L-carnitine improved hot carcass weight and reduced linoleic acid content of jowl fat.

Overholt et al. (2016b) fed pelleted or meal diets containing 0 or 30 percent DDGS diets to fresh belly characteristics, fat quality, and bacon slicing yields of finishing pigs. Feeding the 305 DDGS diets reduced belly thickness, flop distance, and initial belly weight, while increasing belly fat IV by 7.1 units, compared with feeding 0 percent DDGS diets. However, feeding DDGS diets had no effect on bacon slice yields or slices per kg. These results suggest that although feeding 30 percent DDGS diets resulted in thinner, softer belies than pigs fed no DDGS, and feeding meal or pelleted 30 percent DDGS diets had no effect on commercial bacon slicing yield.

Feeding DDGS diets to immunological castrates

Physical castration of male pigs has been a common practice in many countries around the world for decades, and is done to reduce the occurrence of aggressive and sexual behaviors of male pigs and prevent the development of an unpleasant odor, known as boar taint, in pork from male pigs. However, while physical castration is effective in eliminating boar taint in pork, it results in lower feed efficiency, less carcass lean, and increased preweaning mortality. Furthermore, some countries such as the United Kingdom, Ireland and Australia no longer allow physical castration of male pigs due to animal welfare concerns. As a result, Zoetis (Florham Park, New Jersey) has developed and markets an injectable immunological castration product called Improvest (U.S. and Canada), Improvac (Australia and New Zealand), Innosure or Vivax, and is registered in 63 countries and has been used for more than 10 years in more than 50 million pigs worldwide (Bradford and Mellencamp, 2013). The U.S. Food and Drug Administration (FDA) has approved this product as safe to use, and pork derived from Improvest treated pigs is safe to eat because there are no residues that can affect human health. Furthermore, there are no export restrictions of pork from immunologically castrated pigs from using this product (Bradford and Mellencamp, 2013). Its use requires two injections, with the first aDMInistration serving as the priming dose for the male pig's immune system and the second dose, admInistered three to 10 weeks before market, causes suppression of testicular function. Immunological castration of male pigs has many advantages over physical castration including improved growth rate and feed conversion, greater carcass lean and less backfat and can dramatically improve profitability by more than $10 per market hog in the U.S. Therefore, recent studies have been conducted to determine the effects of feeding DDGS diets to immunologically castrated pigs on growth performance, carcass characteristics and meat and pork fat quality.

Asmus et al. (2014b) fed physically or immunologically castrated pigs one of three dietary treatments consisting of 0 percent DDGS, 30 percent DDGS, or 30 percent DDGS diets through day 75 and no DDGS to day 125 (market). Immunologically castrated pigs had reduced carcass yield and feed intake, regardless of dietary treatment, compared with physical castrates, but had improved ADG and gain:feed. Carcasses from immunologically castrated pigs had increased IV of carcass fat depots, but increasing the length of feeding duration before market after the second Improvest injection resulted in carcass fat IV to be similar to that of physical castrates. Regardless of castration method, withdrawing DDGS from the diet before slaughter reduced the negative impact on carcass yield and improved carcass fat firmness.

Little et al. (2014) evaluated belly quality of finishing pigs fed 0 or 30 percent DDGS diets, and withdrawing DDGS from the diet 5 weeks before slaughter improved belly firmness in immunological castrates (IC) and physical castrates (PC). There were no differences in bacon aroma, off-flavor, flavor or saltiness between IC and PC pigs slaughtered five or seven weeks after the second improves dose regardless of DDGS feeding program. These results indicate that immunological castration was as effective as physical castration in eliminating boar taint in bacon when feeding 30 percent DDGS diets or withdrawing DDGS from the diet before slaughter at five or seven weeks after aDMInistering the second dose of Improvest.

Similarly, Tavárez et al. (2014) evaluated carcass cutability and commercial bacon slicing yields of PC and IC barrows slaughtered at two time points and fed 0 or 30 percent DDGS diets and withdrawing DDGS from the diet after the second Improvest dose until slaughter. Carcass traits, cutting yields, and fesh belly characteristics were minimally affected by DDGS feeding strategy. There was no effect of DDGS feeding strategy on boneless carcass cutting yields for IC pigs, but these cutting yields were reduced in PC barrows fed the control diets. Belly fat IV was geater in pigs fed 30 percent DDGS diets compared with the control diet, and although bacon slicing yiled was reduced in IC barrows fed none and 305 DDGS diets compared with PC barrows, withdrawing DDGS from the diet before slaughter improved bacon slicing yields of IC barrows.

Most recently, Harris et al. (2017a,b) and Harris et al. (2018) evaluated the effects of different corn DDGS feeding strategies and time intervals between the second Improvest dose and slaughter of IC pigs on growth performance, carcass composition, primal cutout, pork lean quality as well as belly and pork fat quality. Dietary treatments included feeding corn-soybean meal diets (CON), gradual decrease (GD) in dietary DDGS inclusion rate (40, 30, 20, and 10 percent) in phases 1 to 4, respectively, feeding 40 percent DDGS diets in phases 1, 2 and 3, and the removing DDGS from the diet in phase 4 (WD) or feeding 40 percent DDGS during the entire four-phase growing finishing feeding period (NCON). Pigs were admInisted the second dose of Improvest at nine, seven or five weeks before slaughter.Feed intake of IC pigs fed 40 percent DDGS diets may have been limited by the high fiber content and the age of pigs when the second dose of Improvest was admInistered, and the withdrawal of DDGS from the diet (WD) before slaughter resulted in a rapid increase in feed intake. Overall, the GD feeding strategy was slightly more effective than the WD feeding strategy in maintaining ADFI, ADG and gain efficiency similar to those fed CON. Using the GD and WD feeding strategies improved carcass dressing percentage and resulted in intermediate carcass primal cut yields and pork loin quality compare with pigs fed CON and NCON feeding strategies. Increasing the time interval of the second Improvest dose before slaughter reduced IV in all carcass fat depots and increased belly thickness, and using the GD and WD feeding strategies also reduced IV in all carcass fat depots.

Effects of Feeding DDGS on Swine Health

There is some evidence that feeding DDGS to swine has beneficial effects on gut health of pigs infected with Lawsonia intracellularis (Whitney et al. 2006a,b), but the mechanisms of these effects are unknown because there is limited information on how feeding DDGS may affect the intestinal microbiota of pigs and their susceptibility to infection or colonization with pathogens. Tran et al. (2012) fed diets containing up to 30 percent DDGS to weaned pigs and showed that there was an increase in microbial similarity and a decrease in microbial diversity and richness in the gastrointestinal tract and suggested that these effects may be associated with microbial ecosystem instability. Furthermore, feeding DDGS diets had no effect on serum immunoglobulin concentrations. Rostagno et al. (2013) conducted two experiments to determine if diets containing 20, 30 or 40 percent DDGS affected susceptibility, intestinal levels, and shedding of Salmonella. In one of these experiments, pigs infected with Salmonella and fed the control diet without DDGS, had higher Salmonellaa shedding frequency than pigs fed the 30 percent DDGS diet, but the overall responses suggest that diets containing DDGS did not alter the susceptibility to Salmonella colonization in growing-finishing pigs. Saqui-Salces et al. (2017b) showed that feeding diets containing DDGS modulated intestinal cell differentiation by promoting goblet cells and altering expression of nutrient receptors and transporters in growing pigs.

The Porcine Epidemic Diarrhea virus (PEDV) had devastating effects on pig mortality in the U.S. in 2013 and led to extensive investigations to determine its survival, along with other corona viruses (transmissible gastroenteritis virus – TGEV; porcine delta corona virus - PDCoV) in feed and feed ingredients, and the effects of various feed additives on their survival. Dee et al. (2015) showed that PEDV survival in feed varies among types of ingredients and appears to survive the longest in soybean meal, but applying a formaldehyde-based liquid treatment caused virus inactivation in all ingredients. Similarly, Trudeau et al. (2017) evaluated survival of PEDV, TGEV, and PDCoV in various feed ingredients and also showed that PEDV virus survived the longest, and TGEV and PDCoV also had high survival in soybean meal compared to several other ingredients including DDGS. These results suggest that soybean meal is a greater risk factor for transmission of corona viruses via feed than DDGS and other common feed ingredients.

Use of DDGS in Gestation and Lactation Diets

Several recent studies have been conducted to evaluate feeding DDGS to gestating and lactating sows on reproductive and litter performance. Song et al. (2010) fed 0, 10, 20, or 30 percent DDGS diets to mixed-parity lactating sows to determine sow and litter performance, energy and nitrogen digestibility, plasma urea nitrogen and milk fat and protein concentrations. Dietary inclusion rate of DDGS had no effect on DE, ME, nitrogen retention or nitrogen digestibility of the diets. Sows fed the 20 and 30 percent DDGS diets had less plasma urea nitrogen at weaning than sows fed the control diet. No differences were observed for dietary DDGS inclusion rate on sow ADFI and backfat change, but sows fed the 30 percent DDGS diets lost more body weight than sows fed the control diet. Furthermore, preweaning mortality of piglets, litter weight gain and piglet ADG were not affected by dietary DDGS inclusion rate. The results from this study showed that feeding diets containing up to 30 percent DDGS had no effect on sow and litter performance, DE and ME of the diets, nitrogen digestibility, and milk composition compared to feeding a corn-soybean meal control diet, suggesting that feeding up to 30 percent DDGS diets to lactating sows will result in satisfactory sow and litter performance.

Wang et al. (2013) determined the effects of feeding 0, 20, or 40 percent DDGS diets to second and third parity sows during the last 20 days of gestation through a 21 day lactation on sow and litter performance, and colostrum and milk composition. No differences were observed for sow average gestation length, wean-to-estrus interval, sow ADFI, lactation backfat and body weight change regardless of dietary DDGS inclusion rate. Furthermore, there were no effects of dietary DDGS inclusion level on total number of pigs born and born alive, average birth weights, pigs weaned per litter, or piglet ADG during lactation. No differences were observed in total solids, protein, fat and lactose content of milk from sows fed the DDGS diets compared to those fed the corn-soybean meal control diet. These results indicate that sows can be fed diets containing 40 percent DDGS in late gestation and lactation when diets (0.87 percent lysine) are supplemented with 5.2 g lysine/kg to replace all of the soybean meal in the diet, without affecting sow and litter performance or colostrum and milk composition.

Li et al. (2014) evaluated the effects of feeding 0 or 40 percent DDGS diets during gestation and 0 or 20 percent DDGS diets during lactation, when housed in individual stalls or group pens during gestation, on sow and litter performance and sow longevity over three reproductive cycles. Feeding DDGS diets over three reproductive cycles had no effect on sow longevity, but decreased litter size and sow productivity compared to feeding corn-soybean meal diets with no DDGS. However, the detrimental effects of housing sows in group pens during gestation on sow productivity were more evident when fed the corn-soybean meal diets compared to when feeding the DDGS diets.

Greiner et al. (2015) conducted three experiments to evaluate feeding 0 or 10 percent DDGS diets to gestating sows and 0, 10, 20 or 30 percent during lactation (Experiment 1), and 0 or 40 percent DDGS diets during gestation and 20, 30, 40 and 50 percent DDGS diets during lactation (Experiments 2 and 3) on sow and litter performance. The overall results from these studies suggest that feeding 40 to 50 percent DDGS diets to sows during lactation may reduce feed intake and litter performance, but feeding diets containing up to 30 percent DDGS during lactation results in acceptable sow and litter performance.

Corn DDGS has relatively high concentrations of unsaturated fatty acids, which may impact the vitamin E status of piglets and sows fed DDGS. Therefore, Sheltonet al. (2014) conducted a study to determine the α-tocopherol concentration in plasma, milk and pig body tissues when gestating sows were fed 40 percent DDGS diets from breeding to day 69 of gestation and supplemented with 44 or 66 mg/kg DL-α-tocopheryl acetate or 11, 22, 33 or 44 mg/kg D-α-tocopheryl acetate. Supplemental vitamin E was fed from day 70 of gestation through weaning. Results from this study showed that the bioavailability of D-α-tocopheryl acetate relative to DL-α-tocopheryl acetate varies depending on the response crieteria considered, but is greater that the suggested potency value of 1.36.

Song and Shurson (2013) showed that the corn oil in DDGS sources can be peroxidized, which may potentially create oxidative stress when adding at high dietary inclusion rates in sow and pig diets. L-carnitine is important in cell metabolism and regulates mitochondrial transport of long-chain free fatty acids to produce ATP by β-oxidation. Commercial sources of L-carnitine are available, and when supplemented in sow diets and has been shown to improve reproductive performance and milk production, as well as providing antioxidant, anti-inflammatory and other protective functions of the gastrointestinal tract (Ramanau et al., 2004; Ramanau et al., 2005; Musser et al., 2005). Wei et al. (2016) fed 0 or 25 percent DDGS gestation diets and 0 or 40 percent DDGS lactation diets containing 0 or 100 mg/kg L-carnitine in gestation and 0 or 200 mg/kg during lactation. Results of this study showed no effects of feeding DDGS diets to gestating and lactating sows on intestinal barrier functions of their offspring, but supplementing diets with L-carnitine improved intestinal barrier functions of newborn and weaned piglets. The total number of eubacteria in the gastrointestinal tract of weaned pigs was increased by L-carnitine supplementation in the corn-soybean meal diet, but supplemental L-carnitine had no effect when added to the DDGS diet.

Li et al. (2013) determined the effects of feeding 0 or 40 percent DDGS diets during gestation to sows in a group-housed system with electronic sow feeds or individual stalls during gestation on stereotypic and aggressive behaviors. Sows housed in group pens and fed the 40 percent DDGS diet fought for longer periods of time, tended to fight more frequently and had greater salivary cortisol levels (indicator of increased stress) at mixing than sows fed the control corn-soybean meal diet. However, sows housed in individual gestation stalls and fed the 40 percent DDGS diet, spent more time resting, spent less time performing stereotypic behaviors and had lower salivary cortisol concentrations (less stress) compared to sows fed the corn-soybean meal diet with no DDGS. These results suggest that feeding 40 percent DDGS diets may reduce welfare of sows when housed in group pens, but improve welfare of sows when housed in individual gestation stalls.

Conclusions

The extensive amount of research that has been conducted during the past several years has resulted in dramatic improvements in nutritionists ability to effectively use corn DDGS at relatively high diet inclusion rates in precision nutrition feeding programs to reduce feed cost while maintaining acceptable growth, reproduction, carcass and meat quality. Prediction equations have been developed to accurately estimate the ME and SID amino acid content of DDGS sources with variable oil content for swine, as well as for managing diet formulations to achieve desired pork fat quality. By using accurate ME, NE and digestible amino acid and phosphorus values when formulating DDGS for all swine production phases, high diet inclusion rates (up to 30 percent) in all phases of production. In fact, the current trend in the U.S. is to adjust and balance the digestible threonine and branch chain amino acid content of diets containing more than 30 percent DDGS for nursery and growing-finishing pigs diets to achieve equal growth performance and carcass composition compared to feeding conventional corn-soybean meal diets. The reduction in pork fat firmness can be minimized by feeding reduced-oil DDGS sources, withdrawing DDGS from the diet three to four weeks before slaughter, or using the most accurate pork fat quality prediction equations to put formulation constraints in DDGS inclusion rates in markets where pork fat quality is a concern. Evidence also suggests that gestating sows can be fed diets containing up to 50 percent DDGS with no detrimental effects on sow and litter performance if the source is free of mycotoxins, and in doing so, it may improve the welfare of sows housed in individual gestation stalls.

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CHAPTER 22

Pelleting DDGS Diets for Swine

Introduction

THE USE OF HIGH DIETARY INCLUSION RATES (GREATER THAN 30 PERCENT) OF DDGS in U.S. swine diets has resulted in significant feed cost savings for many years. However, the majority of swine DDGS diets in the Midwestern U.S. are fed in meal form. When DDGS diets must be pelleted, DDGS is often limited to 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 swine 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 swine (Miller, 2012) feeds 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 that are to be pelleted have lower average particle size than those fed in meal or mash form to increase pellet durability (Wondra et al., 1995a). 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 is 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 that are collected in the cooler are returned to the pellet chamber to be subsequently reformed into pellets. For some swine 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 that pellets will remain intact from the time of manufacturing until they are consumed. 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 15 kilowatt hours per metric ton should be a reasonable goal for pelleting swine diets. 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 that is 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 that are 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).

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 that increasing steam pressure resulted in only small improvements in PDI, whereas Thomas et al. (1997) reported that 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 that 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. Knauer (2014) evaluated the effects of regrinding soybean meal (1,070 vs. 470 µm) and DDGS (689 vs. 480 µm) and the addition of 0 or 30 percent DDGS to swine finishing diets on pellet quality. Results of this experiment showed that adding 30 percent DDGS to diets improved modified PDI by 9.5 percent, regrinding soybean meal improved modified PDI by 4.7 percent, but regrinding DDGS had no effect on modified PDI. Knauer (2014) also evaluated the effects of pelleting diets containing two particles sizes of DDGS (640 vs. 450 µm) and two levels of pellet fines on growth performance of finishing pigs and observed no effects. These results suggest that reducing DDGS particle size by regrinding does not improve pellet quality.

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 at a low cost, rather than manipulating formulations to optimize PDI.

Starch content of swine 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 that 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 that 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 that has been 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 that the results from both methods were correlated, and Fahrenholz (2012) also reported that 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 that 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. DDGS 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

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)

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 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 size ingredients and diets may improve lubrication of the pellet die and increased production rates.

Pelleting DDGS Diets for Swine

Limited studies have been conducted to evaluate pellet durability of swine diets when DDGS is added, and results are inconsistent. Fahrenholz (2008) observed a reduction in PDI as DDGS inclusion rates increased from 0 percent (90.3 PDI), 10 percent (88.3 percent PDI) and 20 percent (86.8 percent), but suggested that the practical significance of this slight decrease in PDI was of minimal practical importance. Stender and Honeyman (2008) observed a more dramatic decrease in PDI (from 78.9 to 66.8) when comparing pelleted diets containing 0 percent and 20 percent DDGS. However, Feoli (2008) showed that adding 30 percent DDGS to corn-soybean meal swine diets increased PDI from 88.5 to 93.0. Farhenholz et al. (2008) used a pellet die that measured 3.97 mm × 31.75 mm, and a conditioning temperature of 85°C, and found that as DDGS levels increased, PDI values and bulk density decreased. De Jong et al. (2013) found no differences in PDI values (93.3 to 96.9), percentage of fines (1.2 to 8.0 percent), and production rate (1,098 to 1,287 kg/hr) among pelleted corn-soybean diets and 30 percent DDGS diets for nursery pigs using a pellet die of 3.18 mm × 3.81 mm. The inconsistent results from these studies suggest that there are likely interactions among processing variables that may have contributed to difference in PDI of DDGS diets among these studies.

One of these factors may be lipid content of DDGS. As previously discussed, lipid content of diets and feed

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 content increases pellet quality	N/A
Fat	Greater than 2 percent lipid content decreases pellet quality	High lipid content increases production rate
Fiber	High fiber content may 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

ingredients affects pellet quality and production rate. Due to partial corn oil extraction being used by the majority of U.S. ethanol plants, oil content of DDGS sources varies from 5 to 13 percent. To evaluate the effect of DDGS oil content on PDI of DDGS diets for swine, Yoder (2016) evaluated the effects of adding 15 or 30 percent reduced-oil, and 15 or 30 percent high-oil DDGS to corn-soybean meal swine finisher diets. Diets were pelleted using conditioning temperatures of 65.6°C or 82.2°C and a 4.0 mm × 32 mm die. Throughput was maintained at a constant rate of 680 kg/hr. Pellet quality was evaluated using 4 pellet durability tests (standard PDI, ASABE S269.4, 2007; modified PDI using three 19-mm hex nuts; Holmen NHP 100 for 60 seconds; Holmen NHP 200 for 240 seconds). Diet inclusion rate (15 or 30 percent) of DDGS and conditioning temperature had no effect on PDI, but PDI was greater for diets containing reduced-oil DDGS (88.0 percent) compared with high oil DDGS (82.8 percent). Furthermore, the method used to determine pellet quality dramatically affected PDI, where the highest value was obtained for standard PDI (95 percent), followed by modified PDI (91 percent), Holmen NHP 100 (89 percent) and Holmen NHP 200 (67 percent). The results of this study indicate that relatively high PDI can be achieved in corn-soybean meal-based swine finishing diets containing up to 30 percent DDGS, and adding reduced-oil DDGS improves PDI by about five percentage points compared with adding high-oil DDGS to the diet. However, caution should be used when comparing PDI values among studies because the use of various PDI test methods can lead to differences in interpretation of acceptable PDI.

Effects of pelleting DDGS diets on energy and nutrient digestibility

Pelleting swine diets has been shown to improve digestibility of starch (Freire et al., 1991; Rojas et al., 2016), lipid (Noblet and van Milgen, 2004; Xing et al., 2004), as well as dry matter, nitrogen and gross energy (Wondra et al., 1995a). Pelleting nursery pig diets containing 30 percent DDGS improved apparent total tract digestibility of dry matter, organic matter, gross energy and crude protein compared to feeding a meal diet (Zhu et al., 2010). More recently, Rojas et al. (2016) evaluated the effects of extruding and pelleting a corn-soybean meal and corn-soybean meal-25 percent DDGS diets on energy and nutrient digestibility. As shown in Table 3, pelleting and extrusion improved apparent ileal digestibility of gross energy, starch, crude protein, dry matter,

Table 3. Apparent ileal digestibility (percent) of gross energy, starch, crude protein, dry matter, organic matter, acid-hydrolyzed ether extract, and amino acids in corn-soybean meal diets with and without DDGS and soybean hulls (adapted from Rojas et al., 2016)

Nutritional Component	Type of Processing			
	Meal	Pelleted	Extrusion	Extrusion + Pelleting
Gross energy	66.2^{d}	68.4^{c}	72.7^{a}	71.0^{b}
Starch	96.4^{b}	97.7^{a}	98.0^{a}	98.4^{a}
Crude protein	72.5^{b}	73.6^{b}	77.9^{a}	76.6^{a}
Dry matter	63.5^{d}	65.3^{c}	69.6^{a}	67.9^{b}
Ash	21.7^{c}	24.^{4b}c	32.4^{a}	27.4^{b}
Organic matter	66.2^{c}	67.9^{b}	71.9^{a}	70.4^{a}
Amino acid %				
Arg	88.3^{b}	88.6^{b}	91.6^{a}	91.1^{a}
His	83.1^{b}	84.9^{a}	85.8^{a}	85.6^{a}
Ile	78.8^{c}	81.3^{b}	84.3^{a}	83.7^{a}
Leu	82.2^{c}	84.9^{b}	87.1^{a}	86.4^{a}
Lys	78.0^{c}	79.6^{b}	81.8^{a}	80.9^{ab}
Met	83.3^{c}	86.5^{b}	87.7^{a}	86.7^{ab}
Cys	66.7	68.6	67.9^{a}	67.6
Phe	81.2^{c}	83.9^{b}	87.3^{a}	86.5^{a}
Thr	70.9^{c}	73.3^{b}	75.7^{a}	74.7^{ab}
Trp	78.1^{c}	80.5^{b}	83.2^{a}	83.4^{a}
Val	75.6^{c}	78.4^{b}	80.5^{a}	79.9^{a}

^{a,b,c,d} Means within a row lacking a common superscript letter differ (P less than 0.05) ash, acid hydrolyzed ether extract and amino acids. The greatest improvement in digestibility for most nutrients was achieved with extrusion, and the combination of extrusion and pelleting generally did not improve digestibility of nutrients beyond that obtained with extrusion. Several other studies have shown that apparent ileal digestibility of amino acids improves with pelleting and extrusion (Muley et al., 2007; Stein and Bohlke, 2007; Lundblad et al., 2012), but this is not always the case (Herkleman et al., 1990).

For the diet containing DDGS, pelleting increased ME content by 97 kcal/kg dry matter, extruding increased ME by 108 kcal/kg dry matter, but the combination of extruding and pelleting did not improve ME content compared with feeding it in meal form to growing pigs (Rojas et al., 2016; Table 4). Similarly, pelleting the corn-soybean meal diet improved ME content by 81 kcal/kg dry matter, and extruding and pelleting increased ME content by 89 kcal/kg, but extrusion alone did not improve ME content.

Effects of pelleting DDGS diets on growth performance

Several studies have shown that an improvement in feed conversion (Wondra et al., 1995a; Nemechek et al., 2015) and growth rate (Wondra et al., 1995a; Myers et al., 2013; Nemechek et al., 2015) when feeding pelleted diets compared to meal diets to swine. A reduction in feed intake is often observed when feeding pelleted diets compared to meal diets, which has been attributed to a reduction in feed wastage (Skoch et al., 1983; Hancock and Behnke, 2001) and improved energy digestibility (NRC, 2012). Feeding pelleted diets containing 15 percent DDGS had no effect on ADG, reduced ADFI and improved feed conversion compared with feeding 15 percent DDGS diets in meal form to growing-finishing pigs. However, when pelleted diets containing 30 percent DDGS were fed to growing-finishing pigs, there was a trend for improved overall growth rate with no effect on feed intake, and feed conversion was improved compared with feeding meal diets (Fry et al., 2012; Overholt et al., 2016).

Effects of pelleting DDGS diets on carcass composition and yield

Several studies have shown no effect of feeding pelleted or meal diets on carcass characteristics (Wondra et al., 1995a; Myers et al., 2013; Nemechek et al., 2015), but some studies have shown an increase in carcass yield (Fry et al., 2012), as well as increased backfat and belly fat (Matthews et al., 2014) when feeding pelleted diets to pigs. In a recent study, De Jong et al. (2016) compared the effects of feeding pelleted or meal diets containing 15 percent DDGS and showed no differences in hot carcass weight, carcass yield, backfat depth loin depth and percentage carcass lean. In contrast, Overholt et al. (2016) fed pelleted diets to growing-finishing pigs and reported an increase in hot carcass weight, 10th rib backfat thickness and reduced percentage of carcass lean compared with pigs fed meal diets, but there was no effect of DDGS diet inclusion rate (0 or 30 percent), nor were there any effects on loin muscle quality. Although feeding pelleted diets reduced the weight of the gastrointestinal tract and improve carcass yield, feeding diets containing DDGS increased the weight of the gastrointestinal weight and contents resulting in reduced carcass yield.

Effects of pelleting DDGS diets on feed handling and storage

Pelleting DDGS diets is useful for reduce ingredient segregation, improving flowability in bins and feeders, and reducing sorting of different size particles of diets by pigs in feeders (Clementson et al., 2009; Ileleji et al., 2007).

Effects of pelleting DDGS diets on feed contaminated with mycotoxins

Frobose et al. (2015) evaluated the effects of pelleting conditions (conditioning temperatures of 66°C and 82°C and retention times of 30 and 60 seconds within temperature) and the addition of sodium metabisulfate to DDGS contaminated with 20.6 mg.kg deoxynivalenol (DON). Pelleting conditions had no effect on DON concentrations but when sodium metabisulfate was added at increasing concentrations to DON contaminated DDGS, DON concentrations were reduced. When DON-contaminated DDGS diets containing sodium metabisulfate were pelleted and fed to nursery pigs, ADG and ADFI were increased. These results suggest that adding sodium metabisulfate to DON-contaminated DDGS prior to pelleting nursery pig diets is effective in reducing the negative effects of this mycotoxin on growth performance.

Table 4. Metabolizable energy content of a corn-soybean meal diet and a corn-soybean meal-25 percent DDGS diet in meal form or after pelleting (85°C), extruding (115°C), and extruding and pelleting (EP) when fed to growing pigs (adapted from Rojas et al., 2016)

	Corn-soybean meal				Corn-soybean meal-25 percent DDGS			
	Meal	Pelleted	Extruded	EP	Meal	Pelleted	Extruded	EP
ME, kcal/kg	3,868^{d}	3,949^{bc}	3,893^{cd}	3,957^{bc}	3,947^{cd}	4,044^{ab}	4,055^{a}	3,926^{cd}

^{a,b,c,d} Means within a row without a common superscript differ (P less than 0.05)

Effects of pelleting on survival of PED virus in contaminated feed

Porcine epidemic diarrhea virus (PEDV) caused devastating effects by dramatically increasing mortality of young pigs in the U.S. swine industry in 2013. This virus can be transmitted by feed and feed ingredients (Dee et al., 2014; Schumacher et al., 2015). However, PEDV is a heat-sensitive virus and the temperature and time of exposure of swine feeds during the pelleting process may reduce the infectivity of PEDV in complete feeds (Pospischil et al., 2002; Nitikanchana, 2014; Thomas et al., 2015). Cochrane et al. (2017) showed that conditioning and pelleting temperatures greater than 54.4°C appear to be effective in reducing the quantity and infectivity of PEDV in swine feed. In fact, results from Cochrane et al. (2017) showed that pelleting diets inactivated PEDV at a faster rate (30 seconds), and at a much lower temperature, than those (145°C and 10 minutes) reported by Trudeau et al. (2016). It is unknown if pelleting swine diets reduces the quantity and infectivity of other pathogens, but appears to be an effective strategy to partially reduce the risk of transmission of PEDV from feed mills to swine farms.

Pelleting increases diet cost

Pelleting diets increases cost (Wondra et al., 1995b), but this increased cost is acceptable if the economic benefits resulting from improved growth performance and reduced mortality exceeds this added cost. In addition to the cost of pelleting DDGS to ship, there is the potential for DDGS to have to be re-ground in order to be added into a diet, and possibly re-pelleted, which adds more cost.

Low PDI and increased fines may decrease growth performance

Pellets that are produced with low PDI, and therefore have increased amount of fines, may negatively impact swine growth performance. Stark et al. (1993) evaluated the effects of pellet quality on the growth performance of pigs in both the nursery and finishing phases. In the nursery phase, pigs fed a pelleted diet with 25 percent added fines had a 7 percent decrease in gain:feed compared to pigs fed a pelleted diet that was screened for fines. In the finishing phase, increasing the amount of fines in the diet resulted in a decrease in gain:feed, thereby decreasing the advantage of feeding a pelleted diet (Stark et al., 1993). However, Knauer (2014) also evaluated the effects of feeding pelleted diets containing two particles sizes of DDGS (640 vs. 450 µm) and two levels of pellet fines and observed no effects on growth performance of finishing pigs.

Low particle size required for pelleting may increase the incidence of gastric ulcers

Gastric lesions and ulcers are a common problem in swine production (Grosse Liesner et al., 2009; Cappai et al., 2013) and contribute to significant financial losses (Friendship, 2006). Hyperkeratosis, mucosal erosions, and bleeding ulcers have been more commonly observed in pigs fed pelleted diets compared to feeding mash diets (Mikkelsen et al., 2004, Canibe et al., 2005; Cappai et al., 2013; Mößeler et al., 2014; Liermann et al., 2015). Although the reasons for this occurrence are not well-defined, several researchers have suggested that diet particle size is a contributing component (Vukmirovic et al., 2017). Vukmirovic et al. (2017) also indicated that further reduction in particle size occurs during the pelleting process, but concluded that from summarizing all available published studies, swine diets containing less than 29 percent of particles less than 400 µm are low risk for ulcer occurrence. De Jong et al. (2016) reported that when pigs were fed a pelleted meal (with or without 15 percent DDGS) for at least 58 days there was a greater prevalence of stomach ulceration and keratinization compared with pigs that were fed meal diets. However, these authors also observed that alternating between feeding pelleted diets with meal diets during the finishing phase may help maintain improvements in feed conversion while reducing the incidence of stomach ulcerations (De Jong et al., 2016). Similarly, Overholt et al. (2016) fed meal or pelleted diets containing 0 or 30 percent DDGS to growing-finishing pigs and found that pigs fed a pelleted diet had greater gastric lesion scores in the esophageal region compared to pigs that were fed a meal diet, but the addition of 30 percent DDGS to the diets had no effects on the incidence of gastric lesions.

Pelleting may increase lipid peroxidation and reduce vitamin and exogenous enzyme activity

Because the pelleting process involves heat and moisture, these conditions can contribute to increased lipid peroxidation (Shurson et al., 2015) and reduced vitamin activity (Pickford, 1992). Jongbloed and Kemme (1990) determined that when swine diets with phytase activity are pelleted at conditioning temperatures ≥ 80°C, phytase activity is reduced which then leads to reduced phosphorus digestibility. While the pelleting process has many different factors that could affect exogenous activity, as conditioning temperatures increase during pelleting, phytase inactivation also increases (Simons et al., 1990).

Prediction equations to improve pellet quality of DDGS diets for swine

The inconsistent results reported in pellet durability, production rates, and energy usage among published studies for swine and poultry indicate that 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 % 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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CHAPTER 23

Use of Enzymes in DDGS Diets for Poultry and Swine

Introduction

THE DEVELOPMENT AND USE OF FEED ENZYMES for use in animal feeds has been one of the most significant nutritional advances in the past 50 years (Khattak et al., 2006). The global feed enzyme market represents more than $550 million U.S. dollars and it has been estimated in saving the feed industry $3 to 5 billion annually (Adeola and Cowieson, 2011). The feed enzyme market is generally comprised of phytases (60 percent) and nonphytase (carbohydrases and proteases; 40 percent), and the use of these exogenous feed enzymes in swine and poultry diets has been one of the most researched nutritional topics for many years (Adeola and Cowieson, 2011). Phytases have been widely used as an economical and effective replacement of supplemental inorganic phosphorus sources in swine and poultry diets, and are classified as 3- or 6-phytases which is based on which phosphate they initiate catalysis on the myo-inositol nucleus of phytic acid (Adeola and Cowieson, 2011). Furthermore, about 80 percent of the global carbohydrase market is comprised of xylanases and glucanases, with lesser amounts of α-amylase, β-mannanase, α-galactosidase, and pectinases (Adeola and Cowieson, 2011). Almost all of these carbohydrases hydrolyze carbohydrate polymers, resulting in reduced molecular weight oligo- or polysaccharides but no free sugars (Adeola and Cowieson, 2011).

Supplementing exogenous enzymes in swine and poultry diets have numerous potential benefits including: reduction of digesta viscosity to enhance lipid and protein digestion; increase the metabolizable energy content of the diet; increase feed intake, growth rate and feed conversion; decreased size and alter the microbial population of the gastrointestinal tract; reduce water consumption and water content of excreta in poultry; reduce the amount of excreta as well as ammonia, nitrogen and phosphorus content (Khattak et al., 2006). However, several factors determine whether these beneficial effects are realized including: matching the specific enzyme with the appropriate target substrates in the diet; concentrations of antinutritional factors in grain-based diets; spectrum and concentrations of enzymes used; animal species, age and stage of production; characteristics of the microflora in the gastrointestinal tract; and the physiological status of the pig or bird (Khattak et al., 2006). In general, poultry tend to be more responsive to dietary enzyme supplementation than pigs, and young animals are more responsive than older animals (Khattak et al., 2006). Super-dosing (greater than 2,500 FTU/kg feed) has also become a major research topic because several studies have shown additional growth performance benefits compared with conventional does of 500 to 1,000 FTU/kg of feed for both poultry and pigs (Adeola and Cowieson, 2011). The mechanisms of these benefits may be due to greater phosphorus release to restore suboptimal calcium:digestible P; less residual phytate in the diet to serve as an antinutritional factor; and/or the generation of myo-inositol which has vitamin-like properties and lipotropic effects (Adeola and Cowieson, 2011).

Although there is a tremendous wealth of research information on various animal responses and modes of action from feeding various commercial enzymes, it has also created a tremendous challenge for nutritionists to determine the appropriate enzymes to use, optimal conditions for using enzymes and modifications in diet formulation strategies to achieve their potential benefits in swine and poultry diets. Several excellent reviews have been published to summarize the benefits and challenges of using various types of enzymes in swine (Adeola and Cowieson, 2011; de Vries et al., 2012; Kerr and Shurson, 2013; Jha and Berrocoso, 2015; Swiatkiewicz et al., 2015) and poultry (Khattak et al., 2006; Adeola and Cowieson, 2011; Slominski, 2011; de Vries et al., 2012; Ravindran, 2013; Swiatkiewicz et al., 2015; Dida, 2016). However, most of these reviews focused on enzyme responses in swine and poultry diets containing a wide variety of ingredients, and not specifically responses to diets containing DDGS. Therefore, the purpose of this review is to summarize numerous swine and poultry studies that have evaluated the repsonses of various exogenous enzymes in DDGS diets.

Fiber Characteristics of DDGS

Dietary fiber is perhaps the most poorly understood constituent of swine and poultry diets, and is generally described as a complex and highly variable component of plant-based feedstuffs (Figure 1, NRC, 2007). It is important to note that the analytical methods used to characterize the fiber component of animal feeds often overlap or exclude fractions of other distinctly different carbohydrate fractions in a feedstuff. As shown in Figure 1, common analytical methods used to measure complex carbohydrates in high fiber feed ingredients and feeds include: crude fiber, acid detergent fiber (ADF), neutral detergent fiber (NDF), soluble and insoluble fractions of total dietary fiber (TDF), and non-starch polysaccharides (NSP). Each of these fiber methods measures several fractions of complex carbohydrates, but they do not adequately relate to the energy value of feeds for swine. Consequently, our ability to adequately relate analytical measures of fiber to its physiological functions have been problematic. Some fiber types are more digestible than others, and although they cannot be degraded by mammalian enzymes, they can be fermented by bacteria in the hindgut (Grieshop et al., 2001). The fermentable fiber types are often called nonstarch polysaccharides (NSP). Up to 90 percent of the cell walls of plants are made up of NSPs; of which, cellulose, hemicellulose, and pectins are most abundant (Selvendran and Robertson, 1990). Other less abundant NSPs include fructans, glucomannans, galactomannans, mucilages, β-glucans, and gums. Cellulose is found in tightly bound aggregates in plants, while hemicellulose and pectins have sugar side chains that allow them to be more readily degraded during the digestive and lower gut fermetation processes. Lignin is not a polysaccharide, but is a high molecular weight polymer that is not considered a functional dietary constituent because it is indigestible by swine (Grieshop et al., 2001).

To understand the opportunities to improve energy content and nutrient digestion when using enzymes in DDGS diets, we first need to know the NSP composition of the fiber fraction in DDGS. Pedersen et al. (2014) determined the non-starch polysaccharide (NSP) profile of 47 corn and 11 wheat DDGS samples and showed that NSP's represent about 25 to 34 percent of the composition of corn DDGS samples (Table 1), and most of it is insoluble. This suggests that the fiber fraction in corn DDGS has limited digestibility in the small intestine, and limited fermentability in the lower gastrointestinal tracts of swine, poultry and fish. Cellulose represents about 5 to 9 percent of corn DDGS content, and the predominant non-cellulosic polysaccharides are xylose (7.7 percent) and arabinoxylose (12.3 to 17.2 percent), which are also mainly insoluble. The mannose content in corn DDGS (1.7 percent) is substantially greater than found in corn grain, and is likely due to the mannan content in residual yeast cell walls that are present in DDGS. Corn DDGS has greater arabinose (6.2 percent) and uronic acid (1.6 percent) content than wheat DDGS (5.7 and 0.8 percent, respectively), which results in relatively high arabinose to xylose and uronic acid to xylose ratios. This indicates that the fiber (heteroxylan) structure is more complex and variable in corn DDGS compared to wheat DDGS, and therefore, is more difficult to degrade with exogenous enzymes. However, the Klason lignin content, which is indigestible, in wheat DDGS was greater than in corn DDGS samples. Klason lignin is not well defined as a chemical constituent, and may contain protein (Maillard products), residual fat and waxes, and cutin in addition to true lignin. These results suggest that the concentrations of substituted xylan and souluble NSP's are altered during DDGS production from their original structure in corn grain.

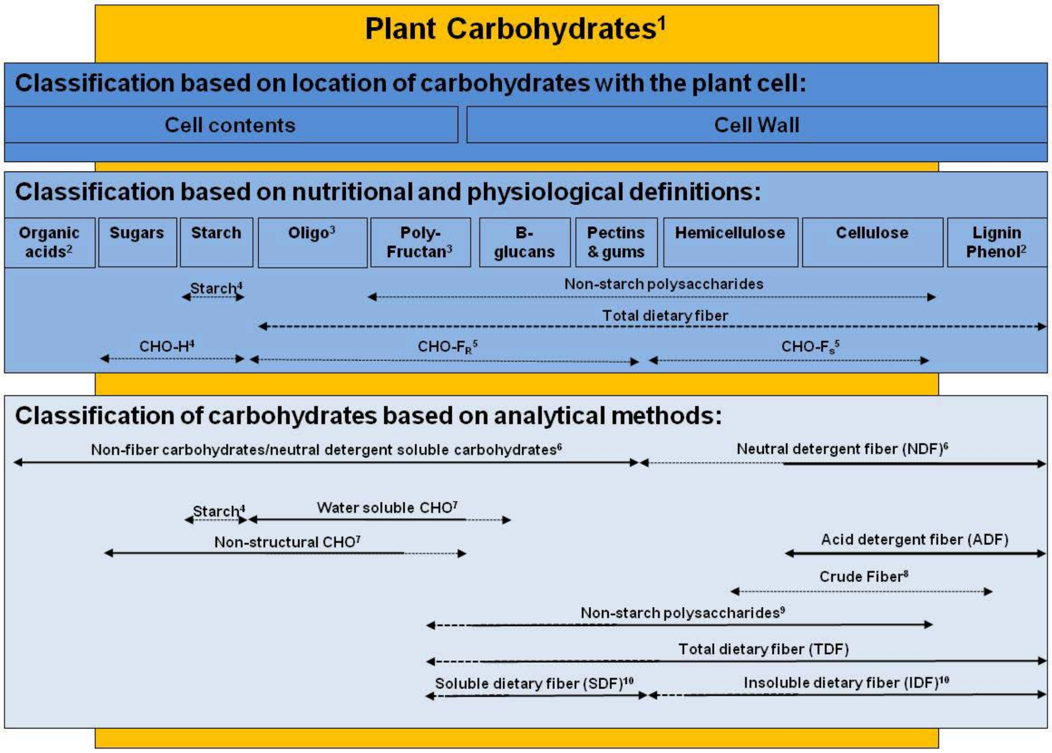

Figure 1. Nutritional and analytical classifications used to characterize plant carbohydrates (adapted from NRC, 2007).

Table 1. Average concentration (percent) and variation in the nutrient and non-starch polysaccharide (NSP) composition of 47 corn and 11 wheat DDGS samples (dry matter basis; adapted from Pedersen et al., 2014)

	Corn DDGS				Wheat DDGS			
	Mean	Range	SD	CV %	Mean	Range	SD	CV %
Moisture	8.7	6.5 – 12.4	0.8	10	7.6	6.8 – 8.7	2.0	2
Crude protein	31.4	27.1 – 36.4	2.1	7	33.4	30.3 – 37.9	2.8	9
Ether extract	9.1	6.5 – 11.8	1.5	17	5.2	4.4 – 6.5	0.8	16
Acidhydrolyzedetherextract	11.1	8.4 – 13.5	1.4	13	7.3	6.5 – 8.8	0.8	11
NDF	35.1	30.2 – 39.7	2.4	7	30.6	27.3 – 34.2	2.6	8
ADF	10.1	8.9 – 11.9	0.6	6	10.5	9.5 – 12.2	0.8	7
Crude fiber	7.7	6.4 – 9.5	0.6	7	6.7	5.5 – 8.8	0.9	14
Starch	6.0	2.9 – 13.9	2.7	45	4.0	<1.0 – 8.8	4.2	103
Total sugars	9.0	5.4 -12.6	1.7	19	9.8	4.6 – 12.4	2.2	23
Ash	7.1	5.4 – 9.0	0.7	9	9.1	8.1 – 10.0	0.4	5
Total NSP	28.3	25.0 - 33.7	2.0	9	26.2	24.2 – 29.1	0.9	4
Soluble NSP	3.1	1.6 - 6.5	0.8	47	6.7	5.3 – 8.0	0.1	2
Cellulose	6.7	5.2 - 9.1	0.8	16	5.0	3.5 – 6.7	1.6	32
Non-cellulosic polysaccharides								
Total xylose	7.7	6.7 - 10.0	0.7	10	8.6	7.0 – 9.3	0.7	8
Soluble xylose	0.6	0.1 - 1.6	0.3	62	2.3	1.5 – 3.2	0.5	22
Total arabinose	6.2	5.6 - 7.2	0.4	7	5.7	5.1 – 6.2	0.0	0
Soluble arabinose	0.7	0.2 - 1.5	0.3	45	1.7	1.2 – 2.2	0.3	15
Total glucose	2.8	2.1 - 4.4	0.4	13	3.3	2.7 – 3.7	0.1	5
Soluble glucose	0.3	0.0 - 1.6	0.4	190	1.1	0.1 – 2.1	1.0	89
Total mannose	1.7	1.2 - 2.0	0.2	12	1.6	1.3 – 1.8	0.2	13
Soluble mannose	0.6	0.4 - 0.9	0.1	19	0.7	0.4 – 0.8	0.1	18
Total galactose	1.5	1.3 - 2.1	0.2	11	1.1	1.0 – 1.2	0.1	11
Soluble galactose	0.3	0.2 - 0.5	0.1	29	0.6	0.4 – 0.7	0.1	18
Total uronic acids	1.6	1.4 - 2.0	0.1	8	0.8	0.7 – 0.9	0.1	12
Soluble uronic acids	0.5	0.3 - 0.6	0.1	11	0.3	0.2 – 0.4	0.0	15
Klason lignin	2.5	1.5 - 4.7	0.7	26	6.6	4.4 – 9.3	2.1	32
Arabinose:Xylose	0.80	0.71 - 0.85	0.0	5	0.66	0.62 – 0.70	0.01	9
Uronic acid:Xylose	0.20	0.16 - 0.23	0.0	8	0.09	0.08 – 0.11	0.0	21

Effects of Adding Exogenous Enzymes to DDGS Diets for Swine

The starch content of DDGS ranges from 3.8 to 11.4 percent, but it is unknown if it is resistant starch or if is digestable and contributes to metabolizable energy content (Table 2). Although most of the dietary fiber in DDGS is insoluble, the apparent total tract digestibility of total dietary fiber varies from 23 to 55 percent. As a result, some of the fiber in DDGS is digested and fermented to contribute significant amounts of energy when feeding DDGS to swine. This likely explains why a measure of fiber (e.g. NDF, TDF) is a significant predictor in recent equations developed to estimate the ME content of reduced-oil DDGS sources for swine (Urriola et al., 2014).

A recent review conducted by Swiatkiewicz et al. (2015) summarized the various responses from adding various enzymes to corn DDGS diets for swine and are summarized in Table 3. In general, the majority of these studies showed improvement in nutrient digestibility when enzymes were added to corn DDGS diets, but this benefit was not usually observed in an improvement in growth performance. Furthermore, several studies summarized in this review evaluated only phytase responses, and not combinations of phytases with carbohydrases and proteases. Several studies summarized in the Swiatkiewicz et al. (2015) review were excluded from Table 3 because they were comparisons with wheat- or wheat-corn blends of DDGS which are not representative of responses to adding enzymes to corn DDGS diets due to different fiber and nutrient characteristics. Furthermore, several studies evaluating enzyme addition to corn DDGS diets for swine have been published since the review by Swiatkiewicz et al. (2015).

To provide a more comprehensive and detailed evaluation of the effects of adding various exogenous enzymes to corn DDGS diets for swine, a meta-analysis was conducted to summarize the overall effects of studies evaluating pig growth performance, with or without phytase, in corn-soybean meal diets (Table 4). Comparisons of growth performance responses from enzyme supplementation in corn-soybean meal and DDGS diets are shown in Table 5, apparent total tract digestibility of nutrients in DDGS diets supplemented with various enzymes are shown in Table 6, and apparent total tract digestibility of fiber components in DDGS diets with various enzymes is shown in Table 7. Data from numerous studies that evaluated the effects of adding various carbohydrases, carbohydrases + proteases, mannases, xylansases, and phytases to corn-soybean meal diets containing DDGS for swine were used in this analysis (Agyekum et al., 2016; Agyekum et al., 2012; Asmus et al., 2012; Barnes et al., 2011; de Vries et al., 2014; de Vries et al., 2013; Graham et al., 2012; Jacela et al., 2010; Jakobsen et al., 2015; Jang et al., 2017; Jones et al., 2010; Kerr et al., 2013; Kiarie et al., 2016; Kiarie et al., 2012; Koo et al., 2017; Li et al., 2012; Moran et al., 2016; Ndou et al., 2015; Passos et al., 2015; Pedersen et al., 2014; Sandberg et al., 2016; Shrestha, 2012; Swiatkiewicz et al., 2013a; Tsai et al., 2017; Widyaratne et al., 2009; Woyengo et al., 2015; Yanez et al., 2011; Yoon et al., 2010).

For all growth performance measures, the overall percentage of improvement in ADG, ADFI, and gain:feed from enzyme supplementation without or with phytase was minimal, which indicates that there are minimal benefits of adding these commercially available enzymes to corn-soybean meal diets (Table 4) and corn-soybean meal diets containing DDGS (Table 5) to justify their cost in commercial swine diets. In fact, the overall ADG and gain:feed responses, when corn-soybean meal (15 comparisons) and DDGS (12 comparisons) diets were supplemented with carbohydrases, were negative (Table 5). However, although the incremental improvements were small, the addition of phytase in

Table 2. Concentration of carbohydrates and apparent total tract digestibility (ATTD) of dietary fiber in corn distillers dried grains with solubles in pigs (adapted from Urriola et al., 2010)

Item	Average	Lowest value	Highest value	SD
Starch, total %	7.3	3.8	11.4	1.4
Starch, soluble %	2.6	0.5	5.0	1.2
Starch, insoluble %	4.7	2.0	7.6	1.5
ADF %	9.9	7.2	17.3	1.2
NDF %	25.3	20.1	32.9	4.8
Insoluble total dietary fiber %	35.3	26.4	38.8	4.0
Soluble total dietary fiber %	6.0	2.36	8.54	2.1
Total dietary fiber %	42.1	31.2	46.3	4.9
ATTD, total dietary fiber %	43.7	23.4	55.0	10.2

Table 3. Summary of responses to adding dietary enzymes to corn DDGS diets for swine (adapted from Swiatkiewicz et al., 2015)

Production Stage	DDGS %	Enzymes	Enzyme Responses	Reference
Nursery	20	Phytase	Increased phosphorus digestibility and reduced phosphorus excretion in manure	Xu et al., 2006a
Growing-finishing	20	Phytase	Increased phosphorus digestibility and reduced phosphorus excretion in manure	Xu et al., 2006b
Sows, late gestation and lactation	15	Phytase	Decreased fecal phytate phosphorus excretion; No effect on sow and litter performance	Hill et al., 2008
Growing-finishing	20	Phytase	Improved dry matter, gross energy and nitrogen digestibility	Lindemann et al., 2009
Growing-finishing	15 to 60	Xylanase, β-glucanase, mannase, cellulose, and protease	No effect on growth performance	Jacela et al., 2010
Nursery	30	Xylanase, β-glucanase, mannanase	No effect on growth performance	Jones et al., 2010
Growing-finishing	10 or 15	Mannanase	Improved growth performance and protein digestibility	Yoon et al., 2010
Growing	50	Phytase	Less improvement in phosphorus digestibility than in corn grain	Almeida and Stein, 2012
Finisher	35 to 50	Xylanase	No effect on nutrient digestibility in 35 percent DDGS, and decreased nutrient digestibility in high DDGS diets	Asmus et al., 2012
Growing-finishing	10 or 15	Xylanase, β-glucanase, phytase, protease, cellulose, and amylase	Tended to improve growth performance	Li et al., 2012
Growing-finishing	7.5 or 10	Xylanase, β-glucanase	Improved nutrient digestibility and growth performance in gilts up to 55 kg in body weight, but not in barrows	Kiarie et al., 2012
Nursery and growing-finishing	30	Multiple commercial products including xylanases, β-glucanases, proteases, and phytases	Minimal and inconsistent improvements in nutrient digestibility of some enzymes and no effect on growth performance in nursery or growing-finishing pigs	Kerr et al., 2013
Growing-finishing	15 or 20	Xylanase and β-glucanase	Tended to improve growth performance, reduced carcass backfat and increased carcass primal cut weights	Swiatkiewicz et al., 2013a
Growing-finishing	30	Xylanase and protease	Reduced odor emission in manure in pigs fed xylanase; protease improved gross energy digestibility	O'Shea et al., 2014
Growing	20	Phytase, xylanase, protease	Increased phytate degradation and improved energy and nitrogen digestibility	Passos and Kim, 2014

combination with carbohydrases, carbohydrases + proteases and xylanases appeared to slightly improve ADG and gain:feed compared with no phytase supplementation in corn-soybean meal diets (Table 4). These responses are in agreement with several published studies indicating that the combination of phytase and carbohydrases generally result in greater growth performance and digestibility responses than either one alone. However, the impact of dietary phytase supplementation on the digestibility of energy has not been consistent. Some studies (Adeola et al., 2004, 2006; Liao et al., 2005; Jendza et al., 2006; Beaulieu et al, 2007) have observed no impact of phytase on energy digestibility, while other studies (Brady et al., 2002; Sheltonet al., 2003; Jendza et al., 2005; Veum et al., 2006) have reported positive effects. Results from Kerr et al. (2010) suggested that if there is an effect of phytase on energy digestibility, it is relatively small in magnitude and highly variable. These disappointing growth performance improvements, or lack thereof, from feed enzyme supplementation are a result of minimal positive effects on dry matter and gross energy digestibility, and negative effects on nitrogen (crude protein) and ether extract (crude fat) digestibility (Table 6). These responses are further confirmed by the relatively minimal overall improvements in apparent total tract digestibility of various fiber fractions in DDGS diets (Table 7).

Table 4. Comparison of the percent change (relative differences) in ADG, ADFI and gain:feed from feed enzyme supplementation in corn-soybean meal diets compared with unsupplemented diets of pigs

Dietary treatment	No. comparisons	ADG % change	ADFI % change	Gain:Feed % change
Without phytase	43	+0.74	+0.43	+0.22
+ carbohydrases	15	-1.10	+0.52	-1.21
+ carbohydrases and proteases	11	+2.03	+1.07	+1.00
+ mannanase	10	+2.35	-0.37	+2.74
+ xylanase	7	+0.33	+0.33	-1.56
With phytase	30	+1.83	+0.38	+1.82
+ carbohydrases	9	-0.14	+2.92	-1.70
+ carbohydrases and proteases	6	+2.22	+1.06	+0.81
+ mannanase	1	+0.47	+0.71	-0.61
+ xylanase	14	+3.03	-1.57	+4.70

Table 5. Comparison of the percent change in ADG, ADFI and gain:feed from feed enzyme supplementation in corn-soybean meal and corn DDGS diets compared with unsupplemented control diets for pigs

Dietary treatment	No. comparisons	ADG % change	ADFI % change	Gain:Feed % change
Corn-soybean meal	43	+0.74	+0.43	+0.22
+ carbohydrases	15	-1.10	+0.52	-1.21
+ carbohydrases and proteases	11	+2.03	+1.07	+1.00
+ mannanase	10	+2.35	-0.37	+2.74
+ xylanase	7	+0.33	+0.33	-1.56
DDGS	30	+1.39	+1.10	+0.58
+ carbohydrases	12	-0.74	+1.42	-1.40
+ carbohydrases and proteases	7	+2.49	+1.92	+1.06
+ xylanase	11	+2.82	+0.24	+2.44

Table 6. Comparison of the absolute differences (percent) change of feed enzyme supplementation in corn DDGS diets compared with unsupplemented control diets on apparent total tract digestibility of nutrients

Nutritional component	No. comparisons	% change
Dry matter	15	+ 0.75
Gross energy	34	+ 0.53
Nitrogen	26	- 0.25
Ether extract	20	- 0.88
Phosphorus	24	+2.15

Table 7. Comparison of the absolute differences (percent) change of feed enzyme supplementation in corn DDGS diets compared with unsupplemented control diets on apparent total tract digestibility (ATTD) of fiber

Fiber component	No. comparisons	% change
ADF	19	- 0.77
NDF	24	+ 0.54
Total arabinoxylose	5	+1.84
Total NSP	5	+4.66
Insoluble NSP	5	+4.84

To improve the effectiveness of enzymes, and other methods of degrading the fiber structure to improve energy utilization in DDGS, a better understanding of the physical structure of fiber is needed. The primary cell wall structure in cereal grains is comprised of a skeletonof cellulosic microfibrils embedded in a matrix of hemicelluloses and smaller amounts of pectins, glycoproteins and hydroxycinnamates. Subsequently as the secondary cell wall continues to develop, p-coumaryl, coniferyl and sinapyl alcohols are co-polymerized to form mixed lignins. (Santiago et al., 2013). The addition of these mixed lignins to the cell wall structure add significant strength to fiber and resistance to degradation.

In corn, the most abundant hemicelluloses are arabinoxylans, which are comprised of a β (1→4)-d-xylan backbone with substitutions of arabinose, glucuronic acid and acetic acid. The hemicellulose is tangled with cellulose microfibrils by hydrogen bonds (Figure 1). These hydrogen bonds give the cell wall greater inaccessibility to degradation (Somerville et al., 2004), but also implies that the removal of arabinoxylans from the surface region of fiber by the addition of xylanases can result in exposure of cellulose microfibrils (crystalline structure), which is highly resistant to acids and enzymatic hydrolysis (Hall et al., 2010). In fact, the apparent ileal digestibility of cellulose (11.9 percent) is less than in other fiber components (37 percent), and the apparent total tract digestibility of cellulose (29.0 percent) is also less than other components of fiber (43.8 percent) in pigs fed wheat DDGS (Pedersen et al., 2015). Therefore, it is possible that the more stable cellulosic microfibrils embed or trap arabinoxylans, resulting in decreased apparent total tract digestibility of fiber and prevent xylanase from accessing its substrates.

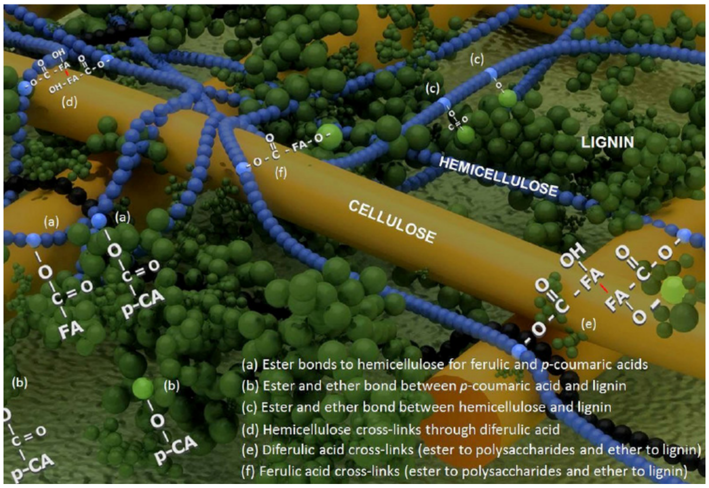

Figure 1. Representation of the secondary cell wall structure in corn (adapted from Santiago et al., 2013)

Furthrmore, understanding the changes in morphology of fiber before and after the degradation processes may be useful in identifying approaches to improve the utilization of fiber in DDGS for pigs. Results from several studies have shown that crystalline celluloses are much more resistant to enzymatic hydrolysis compared to those with low crystallinity (Fan et al., 1980; Zhang and Lynd, 2004; Hall et al., 2010). In addition, the crystallinity and crystal size of natural fiber sources have been shown to increase during thermal processing (Poletto et al., 2014). It is well known that the production of DDGS involves drying temperatures greater than 100 °C as it exits the dryer (Rosentrater et al., 2012). This indicates that the most readily degradable fiber may have already been partially degraded during DDGS production and thus, limits the effectiveness of feed enzyme or other processing technologies in high DDGS diets. In fact, Urriola et al. (2010) showed that variability of fiber digestibility varies among DDGS sources, which may be due to ethanol plants using various processing conditions.

Processing methods can be used to modify plant cell wall structure and improve NSP degradability, but use of common feed processing methods such as grinding and pelleting are inadequate for degrading NSP structures (de Vries et al., 2012). Although hydrothermal pretreatments using acid catalysts have been shown to be effective in degrading lignocellulosic material (Sun and Cheng, 2002), they can cause protein damage and increase acid or mineral content (van den Borne et al., 2012). In contrast, the use of mild acid hydro thermal treatments with maleic acid has been shown to increase solubilization of NSP in DDGS (de Vries et al., 2013). However, although acid extrusion aided in more rapid degradation of NSP, and shifted fermentation to more proximal locations in the gastrointestinal tract, more than 35 percent of NSP in DDGS were not degraded (de Vries et al., 2014). As a result, these authors suggested that enzymes and/or process technologies may be more effective if ester-linked acetyl, feroyl, or coumarol groups of the fiber structure are targeted. Cereal grains, ferulic acid, p-coumaric acid and sinapic acid are involved in coupling of arabinoxylans, cell wall trapped protein and lignin like polymers (Ralph et al., 1995; Bunzel et al., 2004; Piber and Koehler, 2005). Ferulic acid and derivatives are the most important cross-links in grain cell walls and are bound to arabinoxylans and pectins (Bunzel, 2010). Dimers, trimmers and oligomers of ferulic acid cross-link with two or more polysaccharide chains to strengthen the cell wall, but impair enzymatic degradation (Grabber et al., 1998a,b) leading to reduced fiber digestibility in DDGS. In fact, Pedersen et al. (2015) reported that the concentrations of ferulic acid dimers and trimmers were five to six times greater in corn DDGS than in wheat or grain blends of DDGS, indicating that the ferulic acid cross-links in the corn cell wall do not appear to be modified during fermentation and production of DDGS.

Ammonia fiber expansion (AFEX) is one alkaline pre-treatment technology that disrupts the crystalline structure of cellulose and significantly enhances enzymatic digestibility from fiber rich biomass (Mosier et al., 2005; Gao et al., 2010). In ruminants, AFEX treated forages were reported to have improved NDF digestibility when evaluated in vitro with rumen inoculum (Bals et al., 2010). This research group also attempted to optimize AFEX pre-treatment conditions in corn DDGS and reported that almost all cellulose in DDGS was degraded after 72 hours of enzymatic hydrolysis, and released 190 g of glucose dry biomass (Bals et al., 2006). Corn DDGS contains 5.8 percent cellulose and accounts for about 23.3 percent of total NSP (Jaworski et al., 2015). If cellulose of DDGS were hydrolyzed before entering the lower gastrointestinal tract of pigs, it may contribute about 242 kcal/kg DE (Noblet and van Milgen, 2004) to the energy value of DDGS. More importantly, the proportion of arabinoxylans imbedded in cellulose may be exposed and more accessible to degradation from exogenous enzymes, bacteria, organic acids and their combination.

Effects of Adding Exogenous Enzymes to DDGS Diets for Poultry

The addition of feed enzymes to poultry diets have many potential benefits including reduction in digesta viscosity, enhanced digestion and absorption of nutrients, increased AME content, increased feed intake, body weight gain and feed conversion, reduced beak impaction and vent plugging, decreased size of the gastrointestinal tract, alter the microbial population in the gastrointestinal tract, reduce water intake and water content of excreta, reduced excreta output and N and phosphorus excretion, and reduced ammonia emissions (Khattak et al., 2006). In general, the supplementation of carbohydrases in poultry diets containing corn DDGS have been more effective than in pig diets containing DDGS.

A recent review conducted by Swiatkiewicz et al. (2015) summarized the various responses from adding different feed enzymes to corn DDGS diets for poultry, and these results are summarized in Table 8. While the majority of these studies showed some benefit of enzyme supplementation in DDGS diets for broilers and layers for at least a few of the response criteria measured, results were inconsistent.

Table 8. Summary of responses to adding dietary enzymes to corn DDGS diets for poultry (adapted from Swiatkiewicz et al., 2015)

Production Stage	DDGS %	Enzymes	Enzyme Responses	Reference
Broilers, 8–21 days of age	30 or 40	Phytase	Improved phosphorus bioavailability but no consistent effects on ME content and amino acid digestibility	Martinez-Amezcua et al., 2006
Broilers, 1–21 days of age	10	Carbohydrases, protease, phytase	Phytase improved dry matter and N digestibility but enzymes had no effect on growth performance	Olukosi et al., 2010
Broilers, 1–42 days of age	10 or 20	Xylanase	Improved feed intake, body weight gain, and dry matter, protein, and hemicellulose digestibility	Liu et al., 2011
Broilers, 18–23 days of age	30	Multi-enzyme containing xylanase, β-glucanase, mannanase, and phytase	No effect on growth performance or nutrient digestibility	Min et al., 2011
Broilers, 12–21 or 7–21 days of age	7 or 10	Multi-enzyme 1 (xylanase, amylase) Multi-enzyme 2 (xylanase, amylase, protease)	Both multi-enzymes improved ME, and Multi-enzyme 2 improved amino acid digestibility except methionine	Romero et al., 2013
Broilers, 1–42 days of age	12 (starter) or 18 (finisher)	Xylanase, phytase	Combination of enzymes improved growth performance, dry matter and organic matter digestibility, retention of Ca and P, and bone characteristics	Swiatkiewicz et al., 2014b
Layers, 26–68 weeks of age	20	Xylanase and β-glucanase	Reduced some of the negative effects of feeding DDGS on egg production during the second phase of the laying cycle	Swiatkiewicz and Korelski, 2006
Layers, 30–40 weeks of age	5, 10, 15 or 20	Multi-enzyme containing xylanase, β-glucanase, amylase, and protease	Improved egg production and lipid digestibility in 15 and 20 percent DDGS diets	Shalash et al., 2010
Layers, 40–56 weeks of age	7, 15 or 23	Multi-enzyme complex containing xylanase, β-glucanase, amylase, and protease	Improved egg production and feed conversion in 7 and 15 percent DDGS diets, but no effect on egg quality, nutrient digestibility, or hematological and biochemical blood charactersitics	Ghazalah et al., 2011
Layers, 40–52 weeks of age	15	Phytase	No effect on egg production or egg quality	Koksal et al., 2012
Layers, 28–36 weeks of age	5, 10, 15 or 20	Multi-enzyme containing protease, pentosanase, pectinase, cellulose, β-glucanase, amylase, and phytase	Reduced N and phosphorus concentrations in excreta but no effect on egg production or egg quality	Deniz et al., 2013a

Table 8. Summary of responses to adding dietary enzymes to corn DDGS diets for poultry (adapted from Swiatkiewicz et al., 2015)

Production Stage	DDGS %	Enzymes	Enzyme Responses	Reference
Layers, 64–72 weeks of age	10	Phytase	Improvedfeedintakeandfeedconversion, decreased phosphorus concentration in excreta, but no effect on egg production or egg quality	Deniz et al., 2013b
Layers, 20–44 weeks of age	20	Xylanase, phytase	Combination of enzymes improved egg production	Swiatkiewiczetal.,2013b
Layers, 20–44 weeks of age	10 or 15	Xylanase	Improvedeggproductionandeggmass	Bobeck et al., 2014
Layers, 26–55 weeks of age	20	Xylanase, phyase	No effect on femur and tibia bone measurements	Swiatkiewiczetal.,2014a

To provide a more comprehensive and detailed evaluation of the effects of adding various feed enzymes to corn DDGS diets for broilers and layers, a meta-analysis was conducted. The comparison of growth performance responses from adding carbohydrases, carbohydrases and proteases, proteases and xylanases to corn-soybean meal and DDGS diets in broilers is shown in Table 9. Similar to responses for swine, adding carbohydrases to corn-soybean meal and corn-soybean meal-DDGS slightly reduced growth performance of broilers, but adding proteases or xylanases appear to be more effective in improving growth performance of broilers when fed DDGS diets compared with responses from feeding corn-soybean meal diets. Depending on the cost of enzymes and diet cost, these responses suggest that adding xylanases to broilers diets may result in growth performance responses great enough to justify the cost of their use. Although the magnitude of protease responses are also relatively high, limited studies have been published that have shown these effects, and caution should be used when considering the likelihood of achieving similar responses when adding commercial proteases to broiler diets. Furthermore, improvements in AME content and dry matter digestibility from adding xylanases to broiler diets containing DDGS were greater than from only supplementing carbohydrases or proteases, but data are limited (Table 10). Two studies showed an average of 4.5 percent improvement in protein digestibility by adding proteases to DDGS diets for broilers, and the combination of carbohydrases and proteases improved AME and dry matter digestibility in DDGS diets for broilers (Table 10).

Although adding the combination of carbohydrases and proteases, or xylanases, to layer diets generally result in improvements in body weight gain, feed intake and gain:feed in layers, the magnitude of improvement is less than in broiler diets but greater than in corn-soybean meal diets for layers (Table 11). Adding enzymes to layer diets appears to slightly improve egg production, egg weight and egg yolk color, but may negatively effect Haugh units of eggs (Table 12). Based on the results from this meta-analysis, nutritionists can use this summary of responses to determine if the magnitude of improvement in economically important production responses is great enough to justify the cost of adding combinations of carbohydrases and proteases, or xylanases to layer diets.

In summary, the type of carbohydrase, protease or xylanase should be considered in this evaluation to determine the likelihood of achieving these responses under commercial conditions for both broilers and layers. Nutritionists are encouraged to obtain the published references cited in these tables to learn more about the diet formulation and experimental conditions used to achieve these responses before deciding if enzyme supplementation is a wise decision in DDGS diets for broilers and layers.

Conclusions

The supplementation of various feed enzymes in swine and poultry diets containing plant-based feed ingredients for swine and poultry has been studied for many years. Growth performance responses in swine and broilers, and egg production responses in layers, have been inconsistent and are a result of properly matching the target substrates (i.e. non-starch polysaccharides, proteins and phytate) with the appropriate enzymes to degrade them and improve digestibility. In general, consistent improvements in phosphorus and nutrient digestibility have been shown from adding phytase to corn-soybean meal diets fed to swine and poultry, but not for carbohydrases, proteases and xylanases. Corn DDGS has unique chemical characteristics that prevent significant degradation from feed enzymes, but imrovements in energy, protein and fiber digestibility are generally greater for broilers than for swine and layers. However, measurable improvements in energy and nutrient digestibility from feed enzyme supplementation do not necessarily improve growth performance and egg production. Based on the results from this meta-analysis, nutritionists can use this summary of responses to determine if the magnitude of improvement in economically important production responses is great enough to justify the cost of adding various types of feed enzymes to swine, broiler or layer diets. The type of carbohydrase, protease or xylanase should be considered in this evaluation to determine the likelihood of achieving these responses under commercial conditions. Nutritionists are encouraged to obtain the published references cited in this chapter to learn more about the diet formulation and experimental conditions used to achieve these responses before deciding if enzyme supplementation is a wise decision in DDGS diets for swine, broilers, and layers.

Table 9. Comparison of the percent change in ADG, ADFI, and Gain:Feed from feed enzyme supplementation in corn-soybean meal and corn DDGS diets compared with unsupplemented control diets for broilers

Dietary treatment	No. comparisons	Weight gain % change	Feed intake % change	Gain:Feed % change
Corn-soybean meal	16	-1.07	-0.77	0.66
+ carbohydrases	4	-6.13	-4.82	1.41
+ carbohydrases and proteases	3	0.75	-0.64	-1.31
+ protease	1	4.34	8.14	3.64
+ xylanase	8	0.11	0.10	0.65
DDGS	33	2.73	1.18	-1.97
+ carbohydrases	7	-0.70	-1.12	-0.33
+ carbohydrases and proteases	7	1.02	-1.23	-2.16
+protease	2	5.95	1.79	-3.89
+ xylanase	17	4.47	3.04	-2.33

References: Olukosi et al., 2010; Liu et al., 2011; Min et al., 2011; Barekatain et al., 2013a,b,c; Waititu et al., 2014; Campasino et al., 2015

Table 10. Comparison of the absolute differences (percent) of feed enzyme supplementation in broiler diets containing corn DDGS on apparent metabolizable energy and apparent total tract digestibility of nutrients

Enzymes	AME[1]		Dry Matter		Crude Protein		Phosphorus	
	n	%	n	%	n	%	n	%
Carbohydrases	8	+0.07	0	ND	3	-0.29	0	ND
Carbohydrases and proteases	7	+4.21	4	+2.75	5	+1.20	5	-1.82
Proteases	0	ND	2	+1.00	2	+4.50	0	ND
Xylanases	6	+5.83	8	+3.63	8	+2.50	0	ND
Overall	21	+3.09	14	+3.00	18	+1.90	5	-1.82

[1] AME = apparent metabolizable energy

[2] ND = not determined

References: Min et al., 2009; Olukosi et al., 2010; Liu et al., 2011; Min et al., 2011; Barekatain et al., 2013a; Romero et al., 2013; Waititu et al., 2014

Table 11. Comparison of the percent change in body weight (BW), ADFI, and feed conversion ratio (FCR) from feed enzyme supplementation in corn-soybean meal and corn DDGS diets compared with unsupplemented control diets for layers

Dietary treatment	No. comparisons	BW % change	ADFI % change	FCR % change
Corn-soybean meal	4	+0.07	+0.48	+0.51
+ carbohydrases and proteases	4	+0.07	+0.48	+0.51
DDGS	16	+3.52	+0.13	-1.86
+ carbohydrases	2	+1.70	-0.87	-2.64
+ carbohydrases and proteases	11	+4.34	+0.30	-1.61
+ xylanase	3	+1.66	+0.19	-2.26

References: Swiatkewicz et al., 2006; Shalash et al., 2010; Ghazalah et al., 2011; Bobeck et al., 2014

Table 12. Comparison of the absolute differences (percent) of feed enzyme supplementation in corn DDGS diets compared with unsupplemented control diets on egg production and quality

Item	No. comparisons	percent change
Egg production	26	+1.26
Egg weight	26	+ 0.33
Egg yolk color	19	+4.94
Haugh units	12	- 0.12

References: Swiatkewicz et al., 2006; Shalash et al., 2010; Ghazalah et al., 2011; Koksal et al., 2012; Deniz et al., 2013a,b; Swiatkewicz et al., 2013; Bobeck et al., 2014

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CHAPTER 24

DDGS in Sheep and Goat Diets

Introduction

WHILE LIMITED STUDIES HAVE BEEN CONDUCTED TO EVALUATE THE EFFECTS of feeding DDGS to sheep and goats compared with other species, DDGS is an economical and excellent feed ingredient in diets for sheep and goats. The high fiber and low starch content of DDGS provides diet formulation flexibility and allows it to safely partially replace a portion of the forage or grain in diets with reduced risk of rumen acidosis compared to feeding grain-based diets (Held, 2006a,b).

Gestating and Lactating Ewes

Ely et al. (1991) fed 20 crossbred ewes with twin lambs from 14 to 56 days post-partum on fescue-hay based diets to provide 75 to 85 percent of the NRC requirements for protein and energy, a forage to concentrate ratio of 2:1, and diets were supplemented with soybean meal or DDGS. Ewes fed the DDGS supplemented diets lost less weight during lactation, but produced less total milk than soybean meal supplemented ewes. Ewes fed at 75 percent of the recommended nutrient intake level lost more body weight, but milk production was not affected compared to feeding a diet at 85 percent of NRC requirements for energy and protein. Lambs from ewes fed the soybean meal supplemented diet, or the 85 percent of recommended nutrient intake level had improved average daily gain. Neither the soybean meal nor DDGS supplements affected daily milk dry matter, crude protein, ash or lactose content. However, ewes fed the DDGS supplemented diet produced 16.5 percent more milk fat per day. Lambs from ewes fed the soybean meal supplemented or the 85 percent level of recommended nutrient intake used milk nutrients more efficiently than lambs nursing ewes fed the DDGS supplemented diets or the 75 percent of the requirement diet. Ewes fed the soybean meal diet had greater dry matter and crude protein digestibility than ewes fed the DDGS diet.

More recently, when DDGS was used instead of soybean meal as a protein supplement in lactating ewe diets, no differences were observed in ewe body condition score and suckling lamb weight gain (Held, 2006a). A lactation study evaluating the use of DDGS to replace 2/3 of the corn (25 percent of the diet) resulted in a 12 percent improvement in reared lamb growth for ewes nursing triplets, but there were no effects for ewes nursing twin and single lambs (Held, 2006a). A possible reason for the comparative differences between soybean meal and DDGS supplementation in Ely et al. (1991) and Held (2006a) reports may be due to differences in dietary nutrient levels fed and the quality of the DDGS sources used.

Radunz et al. (2011) compared ewe and lamb performance of three winter-feeding gestation systems to crossbred ewes, haylage, limit-fed corn or limit-fed DDGS. At parturition, ewe body weight was heaviest for those fed DDGS, lowest for those fed haylage, and intermediate for those fed corn. Ewes fed corn and DDGS had greater body condition scores at parturition than those fed haylage, and at weaning, ewes fed DDGS had greater body condition scores than those fed corn or haylage rations. Body weight of lambs at birth tended to be heavier from ewes fed corn and DDGS compared to ewes fed haylage, but there was no effect of ewe gestation diet on lamb weaning weight. Body composition of lambs at birth, ewe milk production, as well as preweaning lamb growth rate and mortality were not affected by feeding program. Feeding DDGS reduced feed costs, but ewes had an increased incidence of ketosis prior to parturition. These researchers then evaluated feedlot performance, glucose tolerance and carcass compositions of lambs weaned from ewes fed the 3 winter-feeding programs (Radunz et al., 2011b). Their results showed that the type of mid- to late-gestation ewe diet fed affects maternal plasma insulin concentration. Lambs from ewes fed DDGS tended to have greater insulin response than those from ewes fed corn or haylage diets. This difference in insulin resistance was associated with alternations in fat deposition affecting primarily internal fat. However, these changes in carcass composition likely have small practical significance, but provide evidence that changes in maternal metabolism due to winterfeeding system may have long-term impacts on progeny growth and body composition.

Rams

Although feeding DDGS in diets for growing rams is increasing, only one study has been published to evaluate these effects on male reproductive traits (Van Emon et al., 2013). Suffolk × western white face ram lambs (40 kg in body weight) were fed 0, 15 or 30 percent DDGS diets as a partial substitute for corn for a 116 day feeding period until market weight. Increasing dietary DDGS levels resulted in a linear increase in dry matter intake and ADG, but there were no effects on final body weight, change in scrotal circumference, carcass characteristics, serum testosterone concentrations and spermatozoa motility score. However, spermatozoa concentration linearly decreased with increasing DDGS content in the diets. Since this is the only published study that has evaluated reproductive performance of rams, more research is needed to confirm or refute the results from this study.

Growing-Finishing Lambs

Protein and amino acid utilization of DDGS has been evaluated in growing lambs and results from two studies indicate that it is an excellent protein source. Waller et al. (1980) conducted a lamb metabolism trial to evaluate the effects of feeding combinations of proteins that are slowly degraded in the rumen with urea. Combinations of urea and DDGS were used were used to replace urea as sources of supplemental protein and did not significantly affect dry matter or N digestibility of the diets. Archibeque et al. (2008) demonstrated that feeding DDGS improves amino acid nutrition of lambs consuming moderate quality forages.

Gutierrez et al. (2009) fed Suffolk lambs three dietary levels of DDGS (0, 15 or 30 percent, dry matter basis). Feed intake was similar among DDGS levels, but body weight gain was reduced when lambs were fed the 30 percent DDGS diet (0.221 kg/d) compared with feeding the 0 and 15 percent DDGS diets (0.284 and 0.285 kg/d, respectively), suggesting that a much lower DDGS feeding level (15 percent) be used for lambs compared to the feeding recommendations by Schauer et al. (2008).

McKeown et al. (2010) showed that DDGS from corn, wheat or triticale can replace a mixture of barley grain and canola meal at 20 percent of diet dry matter without adversely affecting dry matter intake, growth rate, or carcass characteristics of growing lambs, but wheat DDGS may reduce gain:feed and triticale DDGS may improve the fatty acid profile of carcass fat. Felix et al. (2012) fed diets containing 0, 20, 40 or 60 percent DDGS to growing lambs and concluded that DDGS can be fed to sheep at up to 60 percent of the diet dry matter without affecting dry matter intake, but higher dietary inclusion rates may decrease ADG. They also observed that feeding high inclusion rates of DDGS may affect marbling score and reduce hot carcass weight. Therefore, they recommended that feeding diets containing 20 percent DDGS of dry matter is optimal. In contrast, Van Emon et al. (2011) showed results that indicate that DDGS can be included in the diets of finishing lambs at levels up to 50 percent of dry matter intake without negatively affecting growth performance, carcass quality, and metabolite concentrations. Similarly, O'Hara et al. (2011) showed that replacing portions of canola meal and barley with 20 percent high or low oil corn DDGS in Canadian Arcott lamb finishing diets was effective in maintaining healthy rumen function, growth performance, and carcass characteristics.

Rambouillet wether lambs were ad libitum fed diets that contained DDGS to replace 0, 33, 66 or 100 percent of cottonseed meal during a 84-day feeding period (Whitney and Braden, 2010). Carcass characteristics were not affected by dietary treatment but the amount of fat in the loin muscle increased with increasing levels of DDGS in the diet. Meat from lambs fed the 100 percent DDGS diet had less cook loss and greater juiciness than meat from lambs fed the 0 percent DDGS diet. These results indicate that partial or complete substitution of DDGS for cottonseed meal in finishing lamb diets provide acceptable carcass characteristics and may enhance sensory traits of meat. In a subsequent study, Whitney et al. (2014) fed 40 percent DDGS diets and increasing amounts of ground juniper hay to Rambouillet lambs during a 91 day feeding trial and showed that reported that DDGS-based diets can reduce total feedlot costs compared to feeding sorghum grain and cottonseed meal-based diets.

Huls et al. (2006) conducted a study to determine the effects of replacing soybean meal and a portion of the corn with DDGS on growth performance, carcass characteristics and the incidence of acidosis, bloat or urinary calculi in wethers fed a high-grain finishing diet with soyhulls as the only source of dietary fiber. Diets were balanced to have similar CP (14.6 percent), ME (3.4 Mcal/kg), and calcium:phosphorus (2:1) and pelleted. Average daily gain, dry matter intake, gain:feed and carcass characteristics were not different between dietary treatments, and no symptoms of acidosis, bloat or urinary calculi were observed. These results suggest that DDGS is an acceptable substitute for soybean meal and a portion of the corn in finishing lamb diets where soybean hulls are the only source of fiber.

Sewell et al. (2009) fed various crop residues (i.e. wheat straw, corn stover, switchgrass, corn fiber and wheat chaff) that were either thermochemically processed or not, in combination with DDGS and showed that nutrient digestibility of these crop residues was improved by thermochemically processing, and these processed crop residues can be fed in combination with DDGS to partially replace corn in ruminant diets.

McEachern et al. (2009) reported results which indicate that DDGS can replace all of the cottonseed meal in lamb finishing diets without negatively growth rate, feed conversion, wool characteristics, and can potentially reduce feed cost/kg of gain. Whitney and Lupton(2010) showed that cottonseed hulls are a good roughage source for lamb finishing diets containing 40 percent DDGS.

Bárcena-Gama et al. (2016) evaluated the effects of feeding diets with and without DDGS (0, 15, 30 or 45 percent) on dry matter intake and digestibility, NDF and ADF digestibility, growth rate and carcass composition of Criollo lambs (29 kg body weight). Feeding diets containing 15 percent DDGS dry matter intake and ADG compared to those fed the control diet with no DDGS, but feeding the 45 percent DDGS diet decreased dry matter digestibility. Furthermore, lambs fed the DDGS diets had greater carcass weight and yield with no difference in backfat thickness.

Similarly, Wrzosówka ram lambs (16 kg) were fed a meadow hay, straw and concentrate diet containing 45 percent DDGS, compared with a concentrate that contained barley, wheat, and soybean meal, for 60 days to evaluate effects on carcass and meat quality (Kawęcka et al., 2017). Dietary treatment had no effect on carcass quality, proportion of cuts, chemical and cholesterol content of meat. The intramuscular fat contained a greater proportion of linoleic acid and conjugated linoleic acid in lambs fed the DDGS diet. These results are consistent with other studies showing that feeding DDGS has beneficial effects on the sensory properties of lamb meat, especially taste.

As discussed in Chapter 15 of this handbook, DDGS contains variable, but sometimes high concentrations of sulfur, and when added to ruminant diets, it can reduce dry matter intake, rumen pH, and cause polioencephalomalacia (PEM). Sulfur-induced PEM involves bacterial reduction of sufate to sulfide and protonation of S^{2-} to hydrogen sulfide gas. When hydrogen sulfide concentrations are elevated in the rumen, the risk of sulfur-induced PEM is increased. Felix et al. (2014) showed that sulfur derived from DDGS is more readily reduced than sulfur from Na_2SO_4 or H_2SO_4. Several recent studies have evaluated the effects of sulfur content in high DDGS diets on rumen characteristics, growth performance and potential mitigation strategies.

Schauer et al. (2008) fed 240 Rambouillet wether and ewe lambs (31.7 kg BW) diets containing alfalfa hay, soybean meal, barley, and a trace mineral supplement, and DDGS replaced barley and soybean meal at 0, 20, 40 and 60 percent of the diet on a dry matter basis. Sulfur concentrations of diets were 0.22, 0.32, 0.47 and 0.55 percent for the 0, 20, 40, and 60 percent DDGS diets, respectively. Thiamin was included at a level of 142 mg/hd/d (dry matter basis) in all rations for the prevention of polioencephalomalacia. Rations were mixed, ground and provided ad libitum. Lambs were harvested after the 111 d feeding trial and carcass data collected. Final weight, ADG, gain:feed, mortality, hot-carcass weight, leg score, carcass conformation score, fat depth, body wall thickness, ribeye area, quality and yield grade and boneless closely trimmed retail cuts were not affected by DDGS inclusion rate, and feed intake increased linearly as level of DDGS inclusion increased. These results suggest that feeding high dietary levels of DDGS results in acceptable lamb performance with no negative effects on carcass traits.

Morrow et al. (2013) fed lambs diets containing 60 percent DDGS with and without 2 percent NaOH to adjust diet acidity and varying amounts of Na_2SO_4 to adjust diets to contain similar total sulfur content (0.60 percent). Lambs fed DDGS treated with 2 percent NaOH had improved dry matter intake, ADG, and final body weight, reduced NDF digestibility, but had no effect on gain:feed compared with lambs fed the untreated 60 percent DDGS diet. Increasing dietary sulfur by adding Na_2SO_4 tended to reduce dry matter intake but did not affect ADG, gain:feed, or final body weight. Rumen H_2S concentrations were not affected by dietary sulfur or NaOH treatment.

Crane et al. (2017) evaluated the effects of feeding 0, 15 or 30 percent DDGS diets, with or without 22 g/metric ton of lasalocid, to Suffolk × Rambouillet lambs (32 kg initial body weight) on growth performance and production of ruminal hydrogen sulfide gas. Increasing dietary DDGS inclusion rate increased ruminal H_2S concentration, linearly reduced dry matter intake and ruminal volatile fatty acid concentrations, but linearly increased gain:feed. The combination of adding lasalocid to diets containing DDGS improved growth performance with no effects on lamb morbidity or mortality.

Neville et al. (2010) conducted two studies to evaluate the effects of increasing dietary levels of thiamine supplementation (0, 50, 100, 150 mg/animal/day) to prevent potential development of polioencephalomalacia (PEM) in lambs fed a finishing diet containing 60 percent DDGS and 0.73 and 0.87 percent sulfur (dry matter basis; Table 1). No clinical cases of PEM were observed, and there were no effects on most carcass charateristics. Feeding the 60 percent DDGS diets had no effect on growth performance in the second study, but dry matter intake was affected quadratically by thiamine supplementation level in the first study. Despite feeding diets

Table 1. Effect of thiamine supplementation on growth performance and carcass characteristics of lambs fed 60 percent DDGS diets (adapted from Neville et al., 2010)

	Control	Low thiamine	Medium Thiamine	High Thiamine
Initial body weight, kg	32.6	32.6	32.5	32.6
Final body weight, kg	62.3	62.8	62.5	60.5
ADG, kg	0.268	0.274	0.272	0.253
ADFI, kg	1.77	1.78	1.98	1.74
Gain:Feed	0.15	0.15	0.14	0.15
Mortality %	1.67	0	0	0
Hot carcass weight, kg	31.4	32.1	31.7	30.9
Leg score[1]	11.3	11.5	11.6	11.1
Conformation score[1]	11.5	11.4	11.6	11.2
Fat depth, cm	0.79	0.86	0.76	0.84
Body wall thickness, cm	2.72	2.99	2.54	2.67
Ribeye area, cm^2	15.6	15.5	15.7	15.7
Flank streaking[2]	337	340	353	336
Quality grade[1]	11.3	11.3	11.5	11.2
Yield grade	3.5	3.8	3.4	3.7
Boneless closely trimmed retail cuts %	44.7	44.3	45.0	46.8

[1] Leg score, conformation score, and quality grade: 1 = cull to 15 = high prime

[2] Flank streaking: 100 to 199 = practically devoid; 200 to 299 = traces; 300 to 399 = slight; 400 to 499 = small; 500 to 599 = modest

containing high sulfur and DDGS content, supplementing thiamine to prevent PEM was unnecessary in this study.

Meat Goats

Very few studies have been published to evaluate the use of DDGS in meat goat diets, but the many positive results reported from feeding high dietary inclusion rates of DDGS to sheep and beef cattle studies should be also applicable to responses expected when feeding DDGS to meat goats. Gurung et al. (2009) fed a 51.6 percent concentrate mix containing 0, 10.3, 20.6 and 31 percent DDGS (dry matter basis) and 48.4 percent Bremuda grass hay diets to 29 kg Kiko × Spanish intact male kids for 57 days to evaluate effects on growth performance and carcass characteristics (Table 2). Initial and final body weight, dry matter intake, ADG and gain:feed were not different among dietary treatments. In addition, plasma urea nitrogen, carcass dressing percentage, rib eye area and body wall fat were not affected by DDGS inclusion rate in the concentrate, but serum cholesterol concentrations increased linearly with increasing dietary DDGS level. These results suggest that up to 31 percent DDGS can be added to meat goat diets without affecting dry matter intake, growth rate, feed conversion and carcass quality.

In a more recent study, castrated male kiko goats were fed diets containing 50 percent Bermuda grass hay and a 50 percent concentrate mix containing 0, 10, 20 or 30 percent reduced-oil DDGS for 84 days to determine the effects on subcutaneous adipose tissues in meat goats (Camareno et al., 2016). Feeding the reduced-oil DDGS diets did not affect total fatty acid content of carcass adipose tissues, but feeding the 30 percent DDGS diet increased the unsaturated fatty acid content in subcutaneous fat.

Dairy Goats

As for DDGS studies in meat goats, only one study has been published to evaluate feeding high amounts (59 percent) of DDGS to dairy goats. Williams et al. (2017) fed late lactation Alpine dairy goats diets containing ground eastern gamagrass (Tripsacum dactyloides L.) hay supplemented with 59 percent DDGS to replace corn and soybean meal. There were no differences in dry matter intake, plasma glucose and non-esterified fatty acids, and milk composition between does fed DDGS compared with those fed corn and soybean meal concentrates, but plasma urea nitrogen increased for goats fed the DDGS diet. These authors concluded that DDGS can replace corn and

Table 2. Growth performance and carcass characteristics of Kiko × Spanish male goat kids fed increasing amounts of DDGS (adapted from Gurung et al., 2009)

	0% DDGS	10.3% DDGS	20.6% DDGS	31.0% DDGS
Initial body weight, kg	28	30	28	30
Final body weight, kg	39	40	36	38
ADG, g	141	134	115	117
Total dry matter intake, g/day	1,017	1,138	1,106	1,003
Concentrate intake, g/day	519	591	575	520
Hay intake, g/day	499	547	531	483
Gain:Feed	0.12	0.12	0.11	0.12
Carcass dressing percentage %	44.6	45.1	44.7	42.2
Rib eye area, cm^2	9.75	10.25	9.50	9.00
Body wall fat, cm	0.94	1.09	0.91	0.97

soybean meal at 59 percent of the diets during a short (14 day) feedings period with no adverse effects on dry matter intake and milk composition during late lactation.

Conclusions

DDGS can be an excellent protein and energy supplement for ewes, rams, and growing-finishing lambs to replace a portion of the corn and soybean meal in the diet. The higher fiber content of DDGS compared to corn and soybean meal may be effective in preventing acidosis in growing-finishing lambs fed high grain diets. Sulfur content should be monitored and managed, especially when feeding high levels of DDGS with moderate to high sulfur levels to avoid polioencephalomalacia. However, several studies have suggested that relatively high sulfur diets can be fed without causing PEM, and thiamine supplmentation may not be necessary. Results from a few studies suggest that differences in performance may be using inaccurate nutritional information of the specific DDGS source being fed when formulating. Conservatively, adding DDGS at a level of 20 percent of growing-finishing lamb diets and 25 percent of lactating ewe diets will provide good performance results, although several studies have shown that DDGS diet inclusion rates of up to 60 percent can provide acceptable growth performance. Limited studies on feeding DDGS diets to meat goats suggest that up to 31 percent DDGS can be added to meat goat diets without affecting dry matter intake, growth rate, feed conversion and carcass quality, and DDGS can replace corn and soybean meal at 59 percent of the diets during a short (14 day) feedings period with no adverse effects on dry matter intake and milk composition during late lactation for lactating dairy goats.

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CHAPTER 25

DDGS in Horse, Rabbit and Dog Diets

Introduction

VERY LITTLE RESEARCH HAS BEEN CONDUCTED RELATED TO FEEDING DIETS CONTAINING DDGS to horses, rabbits and dogs. However, because of the increasing supply and availability of U.S. DDGS, as well as its high quality, relatively low cost and often the low risk of mycotoxins, it has tremendous potential to be used in greater quantities in horse, rabbit, and dog feeds. Unfortunately, there are no recent studies evaluating the effects of feeding reduced-oil DDGS to these animal species.

Horses

Researchers in Germany have estimated the digestible energy in distiller's co-products range from 11.5 to 14.2 MJ/kg (2,747 to 3,392 kcal/kg) of dry matter (DLG, 1995). The relatively high oil content in DDGS allows it to be an important energy source for performance horses (DLG, 1995; Orme et al., 1997). Four studies have been conducted to determine gross energy, dry matter, and nutrient digestibility of DDGS for horses and results are summarized in Table 1.

Leonard et al. (1975) conducted two studies to determine the gross energy (GE), dry matter (dry matter), and crude protein (CP) digestibility of DDGS in mature horses and reported no differences in GE and dry matter digestibility when DDGS was included up to 18 percent of the diet. However, responses were inconsistent for CP digestibility among the two experiments where CP digestibility decreased as DDGS inclusion rate increased in geldings, but increased as dietary DDGS level increased for mature horses. However, Pagan and Jackson (1991) fed pelleted diets containing 0, 5, 10 or 20 percent DDGS to horses, and reported much greater dry matter and CP digestibility than Leonard et al. (1975) and no meaningful effects of DDGS inclusion rate. Bonoma et al. (2008), fed weanling horses completely pelleted diets consisting of 50 percent alfalfa and 50 percent concentrate containing either corn and soybean meal or replacing 30 percent of the concentrate with DDGS. Their results showed a significant reduction in dry matter and CP digestibility when DDGS was fed. Furthermore, due to the high concentration of protein and relatively high protein digestibility in DDGS, Frape (1998) showed DDGS can be an effective partial replacement for soybean meal or dried skim milk powder in horse feeds. In general, perhaps with the exception of feeding DDGS to weanling horses, up to 20 percent DDGS can be used effectively in mature horse diets without negatively affecting dry matter and CP digestibility. These results suggest DDGS is a highly digestible energy source for horses.

Although horses can utilize the nutrients in DDGS quite well, palatability is one of the potential factors that could limit its use. Horses are very sensitive to dietary inclusion of novel feed ingredients. Therefore, Pagan and Jackson (1991) conducted a feed preference trial to determine if palatability is a concern. Horses were fed pelleted diets containing 0 percent, 5 percent, 10 percent or 20 percent DDGS in two tests over six consecutive days. Horses showed no differences in feed preference between diets containing 0 percent, 5 percent or 10 percent DDGS, and horses more frequently preferred the 20 percent DDGS diet compared with pellets containing lower levels of DDGS. These results suggest DDGS can be used effectively in pelleted horse feeds at levels up to 10 percent of the diet, without any negative effects on palatability, and increasing the DDGS dietary inclusion level to 20 percent may actually increase feed preference.

Hill (2002) evaluated eating behavior and feed intake responses of horses fed various proportions of wheat distiller's grains and concentrate at ratios of 1:0, 0.75:0.25, 0.50:0.50, and 0:1. When wheat distiller's grains were offered at a rate of 0.75 of dietary dry matter, and not soaked prior to feeding, there was a significant reduction in the rate of feed ingestion and the number of chews per kg of dry matter. If the concentrate was soaked before feeding, there was an increase in the number of feeding bouts when 0.25 of the concentrate dry matter was replaced with wheat distiller's grains. However, feed consumption was not affected until 0.5 of the concentrate dry matter was replaced with wheat distiller's grains. Based upon these results, Hill (2002) concluded that wheat distiller's grains can be used as a substitute for other energy and protein ingredients in horse rations, but the dietary inclusion rate depends on the method

Table 1. Summary of gross energy (GE), dry matter (dry matter), and crude protein (CP) digestibility of diets containing DDGS for horses

Age	DDGS %	GE digestibility %	Dry matter digestibility %	CP digestibility %	Reference
Maturegeldings(400kg)	0	43.8	44.1	60.0	Leonard et al. (1975)
	5	40.7	40.1	56.8	
	10	41.8	41.4	54.7	
Mature horses (460 kg)	0	44.7	43.0	35.6	Leonard et al. (1975)
	9.1	43.2	42.1	44.7	
	18.2	38.9	41.5	49.9	
Weanlings (276 kg)	0	-	67.2	64.1	Bonoma et al. (2008)
	15	-	51.1	51,5	
Horses of varying ages	0	-	58.9	69.8	PagenandJackson(1991)
	5	-	57.7	68.3	
	10	-	57.7	67.6	
	20	-	58.7	67.0	

of feed presentation to the horse. Soaking of the concentrate before feeding reduced the level of the distiller's co-product that could be incorporated into the ration to meet the desired amount of dry matter intake.

Only one study has been published to determine the effects of feeding DDGS diets on horse growth performance (Bonoma et al., 2008) fed weanling horses pelleted diets consisting of 50 percent alfalfa and 50 percent concentrate containing either corn and soybean meal or 30 percent of the concentrate replaced with DDGS. Growth rate and feed conversion were not different between the two dietary treatments. However, feeding the DDGS diet resulted in reduced dry matter, protein, acid detergent fiber and neutral detergent fiber digestibility compared to feeding the corn-soybean meal concentrate. Therefore, for weanling horses, less than 30 percent of the concentrate or less than 15 percent of the total diet should be replaced with DDGS when alfalfa is used as the forage source and comprising 50 percent of the total diet. If a forage source that is lower in quality than alfalfa is used, it may be advisable to use less DDGS as a partial substitute for corn and soybean meal in concentrates fed to weanling horses.

Rabbits

Very little research has been conducted to evaluate the feeding value of DDGS for rabbits. One study was conducted in Spain where researchers compared the nutrient digestibility of wheat bran, corn gluten feed and DDGS in New Zealand White x Californian crossbred rabbits (Villamide et al., 1989). The basal diet contained a low amount of energy (2200 kcal/kg dry matter) and a high energy to protein ratio (25 kcal DE/g digestible protein). Although the fiber content of the diets was similar, energy and acid detergent fiber digestibility was highest for rabbits fed the DDGS diet (74.0 percent and 58.3 percent, respectively) compared to rabbits fed diets containing wheat bran (59.4 percent and 9.6 percent, respectively) and corn gluten feed (65.0 percent and 27.7 percent, respectively). Furthermore, rabbits fed the DDGS diet had the highest level of protein digestibility (70.1 percent) compared to rabbits fed the wheat bran (66.6 percent) and corn gluten feed (61.4 percent) diets. These results suggest DDGS is a suitable ingredient for rabbit diets and it provides more digestible energy, ADF and protein than wheat bran and corn gluten feed.

Villamide and Fraga (1998) developed equations to predict digestible crude protein from chemical composition of feed ingredients categorized as dry forages (n = 26), cereals and cereal by-products (including DDGS; n = 29), protein concentrates (n = 18), and by-products (n = 22). Crude protein content was the best predictor of digestible protein in cereals and cereal by-products flowed by ADF content resulting in a digestible crude protein equation of y = -10.856 + 0.628 × percent crude protein + 0.224 × percentADF.

Recently, Alagón et al. (2016) determined and compared the nutritional value of DDGS derived from barley, corn, and wheat from bioethanol plants in Spain (and a corn DDGS sample from Brazil) for growing rabbits (Table 2). Barley DDGS had lower dry matter and ether extract (crude fat) digestibility than corn and wheat DDGS, and had lower gross energy digestibility corn DDGS (Spain) and wheat DDGS. As a result, digestible energy values were similar among corn and wheat DDGS sources but greater than for barley DDGS. Furthermore, digestible protein was less in barley DDGS compared with Brazilian corn DDGS and wheat DDGS. It is unknown how U.S. corn DDGS would compare to the sources evaluated in this study, but these results indicated that corn DDGS can provide significant digestible energy and crude protein when added to growing rabbit diets.

Dogs

There are limited studies to evaluate the addition of DDGS to dry, extruded dog foods. Early studies were conducted at the University of Illinois (Allen et al., 1981) to evaluate nutrient digestibility of diets containing DDGS for both adult and immature Pointer dogs. Supplementation of diets with low levels (4 to 8 percent) of DDGS had no effect on the apparent digestibility of dry matter and starch by adult dogs. Adding moderate levels (16.1 percent) of DDGS to the diet decreased dry matter digestibility, but had no effect on starch and energy digestibility. Feeding diets containing high levels (26.1 percent) of DDGS decreased dry matter and energy digestibility, but had no effect on crude protein digestibility in adult dogs. Growing puppies fed diets containing a moderate amount (14.1 percent) of DDGS had lower dry matter and energy digestibility, but digested more acid detergent fiber compared to puppies fed diets containing no DDGS. Nitrogen intake and fecal nitrogen were reduced when DDGS was supplemented in the diet, but there was no effect on urinary nitrogen, total nitrogen excretion, absorbed nitrogen or nitrogen retention.

A subsequent study conducted by Corbin (1984) showed that feeding a diet containing 10 percent DDGS to growing puppies had no effect on food intake, weight gain, gain:feed, increase in body length of final body weight after feeding for 10 weeks. Including DDGS in diets for older, more mature dogs can be advantageous for controlling weight gain because of its high fiber content. Weigel et al. (1997) suggested diets for mature dogs could include up to 25 percent DDGS depending on age and activity level to achieve good intestinal health.

More recently, de Godoy et al. (2009) evaluated the application of DDGS and other novel corn co-products and suggested that they had nutritional properties comparable to common protein and fiber sources used in animal nutrition. Silva et al. (2016) evaluated dry matter, crude protein, acid hydrolyzed ether extract, organic matter, and gross energy digestibility, with and without the addition of xylanase, and increasing inclusion rates of DDGS in dog diets (Table 3). Increasing diet inclusion rate up to 18 percent tended to slightly reduce energy and nutrient digestibility and metabolizable energy content of diets, but xylanase supplementation improves the digestibility of dry meatter, crude protein and organic matter of DDGS diets. However, adding 18 percent DDGS to dog diets improved palatability of diets for dogs.

Table 2. Apparent digestibility of dry matter (dry matter), crude protein (CP), ether extract (EE), gross energy (GE), digestible energy and digestible protein of DDGS sources fed to growing rabbits (adapted from Alagón et al., 2016)

Measure	Barley DDGS	Corn DDGS (Spain)	Corn DDGS (Brazil)	Wheat DDGS
Dry matter %	64.7^{b}	72.2^{ab}	68.4^{ab}	75.4^{a}
CP %	63.5	65.6	70.4	74.8
EE %	76.7^{a}	92.1^{b}	94.5^{b}	91.5^{b}
GE %	58.2^{c}	71.8^{ab}	65.3^{cb}	75.0^{a}
Digestible energy, MJ/kg dry matter	11.87^{a}	15.89^{b}	14.72^{b}	15.69^{b}
Digestibleprotein,g/kgdrymatter	168^{a}	195^{ab}	221^{b}	263^{c}

^{abc}Mean with different superscripts are different (P less than 0.05)

Table 3. Total tract digestibility of dry matter (dry matter), crude protein (CP), acid hydrolyzed ether extract (AHEE), organic matter (OM), gross energy (GE), estimated metabolizable energy (ME) and fecal dry matter of dogs fed diets containing 0, 6, 12, or 18 percent DDGS with and without xylanase supplementation (adapted from Silva et al., 2016)

	0% DDGS		6% DDGS		12% DDGS		18% DDGS	
Measure	No Enz	Enz	No Enz	Enz	No Enz	Enz	No Enz	Enz
Dry matter %	85.1	85.8	84.1	85.2	81.5	82.6	80.6	83.2
CP %	87.6	88.3	87.3	88.3	85.6	87.8	85.1	87.3
AHEE %	93.0	93.2	92.7	92.8	89.6	90.7	90.0	91.3
OM %	88.5[a]	88.5[a]	88.5[a]	88.0[b]	85.0[b]	87.0[b]	83.1[b]	85.6[b]
GE %	89.6	89.6	89.2	88.3	85.7	87.3	83.6	85.5
ME, MJ/kg	19.55	19.78	19.14	19.41	18.98	18.54	18.89	18.67
Fecal dry matter, g/kg	395	392	363	362	352	352	347	353

[ab]Means with different superscripts within row are different (P less than 0.05)

Conclusions

Based upon the limited research information available, it appears DDGS is a very suitable ingredient for use in horse, rabbit, and dog diets. Current feeding recommendations are shown in Table 4.

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Table 4. Recommended maximum dietary inclusion rates for DDGS in diets for horses, rabbits, and dogs

Species	Maximum DDGS Inclusion Rate
Horses (mature)	Up to 20 percent of the diet
Horses (weanling)	Up to 15 percent of the diet depending on forage quality
Rabbits	Up to 20 percent of the diet
Growing puppies	Up to 10 percent of the diet
Adult dogs	Up to 25 percent of the diet depending on age and activity level

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CHAPTER 26

Impact of Diet Formulation Methods on Assessing Value of DDGS

Introduction

AS DISCUSSED IN MANY CHAPTERS IN THIS HANDBOOK, one of the most important factors for identifying DDGS sources with the greatest nutritional and economic value to maximize diet inclusion rates, minimize diet cost and provide optimal animal performance is to use of accurate energy and digestible nutrient values for the DDGS source being fed. This is essential in precision animal nutrition programs because overestimating energy and digestible nutrient content in DDGS, or any other feed ingredient, can result in reduced growth performance, which is more likely to occur when DDGS is used at high dietary inclusion rates. In contrast, underestimating nutrient content of DDGS can result in feeding excessive nutrients above the animal's requirement, as well as underestimate its economic value and increased nutrient excretion in manure.

Another equally important factor in achieving optimal nutrition in DDGS precision nutrition feeding programs is to use the most advanced methods of diet formulation available for each species. The purpose of this chapter is to summarize the various diet formulation methods that have been used by nutritionists and to provide recommended methods to achieve optimal nutrition and economic value of DDGS diets for all species.

Diet formulation methods

Energy, protein (amino acids), and phosphorus are the three most expensive nutrients provided in animal feeds. Despite the development and use of precision nutrition approaches in diet formulation for various animal species, some nutritionists continue to use less accurate and outdated diet formulation approaches. For example, formulation methods have improved over the years where instead of formulating swine and poultry diets on a crude protein basis, we now formulate diets for these species on a standardized ileal digestible amino acid basis. Furthermore, use of the net energy system instead of metabolizable energy when formulating swine diets provides a more accurate approach for accounting for the true utilizable energy value of diets containing high fiber ingredients like DDGS. Similarly, using standardized total tract digestible phosphorus values are more accurate than using available or total phosphorus values for swine and poultry. These advanced feed formulation approaches have greatly increased our ability to meet the animal's true nutrient requirements.

Diet formulation method affects animal performance and DDGS value and usage. The goal is to formulate diets to meet all of the animal's daily requirements while minimizing the amount of excess energy and nutrients in the diet to minimize cost and nutrient excretion in manure, and support optimal animal health and performance.

It is well accepted that digestible energy (DE) is a more accurate measure of the utilizable energy in a feed than gross energy. Likewise, metabolizable energy (ME) is a more accurate measure than DE and net energy (NE) is a better measure than ME. However, depending on the accuracy and availability of DE, ME or NE values for feed ingredients, level of technological understanding of nutritionists, and knowledge and acceptance of energy requirements using any of these energy systems, diet formulations can vary substantially. Unfortunately, NE values for DDGS are not as well defined as ME values, and ME content has been shown to be highly variable among DDGS sources (see Chapter 20 and 23).

Crude protein is a measure of the nitrogen content of a feed or feed ingredient and does not adequately reflect the amino acid content, digestibility, or quality of the protein in feed ingredients. While crude protein is an acceptable measure when formulating ruminant diets, it is unacceptable to achieve accuracy in meeting the digestible amino acid needs of pigs, poultry, and aquaculture species. In general, crude protein is a useful measure in ruminant diets because the microorganisms in the rumen can convert various forms of nitrogen into the required amounts of microbial protein, with the proper amino acid amounts and balance, to meet the amino acid needs of ruminants. However, measures of rumen degradable and undegradable protein provide more accurate measures of the true nutritional value of protein in ruminant feeds than crude protein. The digestive systems of monogastric animals do not have these capabilities, and therefore, require specific amounts of digestible amino acids in their daily diet. For swine, poultry and aquaculture, formulating diets on a total amino acid basis is more accurate than using crude protein, but much greater accuracy is achieved when these diets are formulated on a digestible amino acid basis. In addition, it is important to monitor and adjust methionine, threonine and tryptophan concentrations relative to lysine to insure proper amino acid balance in DDGS diets for swine, poultry and fish. It is also important to insure that the proper proportion of energy is provided relative to amino acid levels (e.g. kcal of ME or NE/g of digestible lysine). Using digestible amino acid in formulating DDGS diets minimizes the risk of overfeeding protein and amino acids, while minimizing diet cost and nitrogen excretion in the manure.

Similarly, monogastric diets containing DDGS should be formulated on a digestible or available phosphorus basis instead of a total phosphorus basis. By accounting for the relatively high level of available phosphorus in DDGS, the amount of inorganic phosphate supplementation, diet cost and phosphorus excretion in manure can be substantially reduced. Using a digestible or available phosphorus formulation approach in DDGS diets allows for optimizing utilization of the high digestible and available phosphorus content found in DDGS.

A summary of accurate energy and digestible nutrient values of DDGS for beef cattle (Chapter 17), dairy cattle (Chapter 19), poultry (Chapter 20) and swine (Chapter 23) are provided in other chapters of this handbook. Furthermore, prediction equations to dynamically estimate ME and digestible amino acid content of DDGS sources for swine and poultry are provided in their respective chapters. Numerous examples of published studies evaluating diet formulation modifications using DDGS to optimize animal health and performance are also provided in these chapters.

Many examples can be shown to illustrate the impact of diet formulation method on DDGS use based on nutrient variability among sources and formulation method. However, several examples of swine diet formulations have been chosen to show the comparison of using different methods and their implications on achieving the goal of precision swine nutrition. These relative comparisons also have relevance for other livestock and poultry species using nutrient profiles and formulation methods specific to those species, but it is beyond the scope of this paper to give all possible combinations of formulations for various production phases for multiple livestock and poultry species.

Impact of Variation in Energy and Digestible Amino Acid Content on Diet Composition and DDGS Use in Swine Diets

DDGS metabolizable energy (ME) values

Two extreme values for ME content of DDGS were selected from previously published data (Pedersen et al., 2007, and Anderson et al., 2009). The ME content for one DDGS source was 4,334 kcal/kg dry matter while the ME value for another DDGS source was 3,414 kcal/kg dry matter. Diets were formulated on a standardized ileal digestible (SID) amino acid basis and contain identical concentrations of ME (Table 1). The SID amino acid content were based on data from in vivo studies that directly determined the SID amino acid values for specific sources of DDGS, where the SID amino acid digestibility coefficients were estimated to be 63 percent, 82 percent, 71 percent and 69 percent for lysine, methionine, threonine, and tryptophan, respectively. Desired nutrient levels were based on NRC (NRC 2012) requirements for a 45 kg pig with 325 g/d of lean tissue gain. Choice white grease was added to the low ME diet at the expense of corn to meet the energy requirement.

Because of the large difference in ME content of these two DDGS sources, about 3.8 percent of choice white grease (pork fat) was added to the low ME DDGS diet to maintain the same level of dietary ME content as the high ME DDGS diet. Without supplementing the diet with choice white grease, the low ME DDGS diet would likely be inadequate for meeting the pigs' energy requirement unless they increased feed intake. If that were to occur, feed conversion would like be less and pigs would consume excess amino acids and phosphorus relative their requirement. Various supplemental fat sources could be used instead of choice white grease to provide these deficient calories, but regardless of fat source, the addition of supplemental fat to low ME diets can increase the total diet cost. These results show that it is important to know the source of DDGS being used and have accurate estimates of the ME, and preferably, the NE content of DDGS and other ingredients to maximize their energy value in diet formulations and minimize diet cost.

Variability in total and digestible lysine concentrations among DDGS sources

As previously described, total and digestible amino acid concentrations also vary among DDGS sources. To show the importance of using accurate digestible amino values for the DDGS sources being fed, three different diets were formulated to contain 10 percent DDGS (Table 2). Sources of DDGS were selected for use in growing swine diet formulations based on their SID lysine values obtained from previously published data reported by Urriola (2005). Total lysine content ranged from 0.76 percent to 1.02 percent and SID lysine ranged from 0.47 percent to 0.67 percent.

Diets were formulated to provide 10 percent (a very conservative dietary inclusion rate) of each of these 3 DDGS sources to maintain a 0.66 percent SID dietary lysine level (Table 3). Accuracy of SID amino acid values becomes increasingly important as dietary inclusion rates of DDGS increase because DDGS would contribute a greater amount of digestible amino acids to the diet relative to the pig's requirement. These results show that while maintaining DDGS at a constant dietary inclusion rate (10 percent), the amount of corn increased and the amount of soybean meal decreased when high SID lysine DDGS is used instead of low SID lysine DDGS when maintaining constant nutrient

Table 1. Comparison of swine grower diet formulations using high ME (4,334 kcal/kg dry matter) and low ME (3,414 kcal/kg dry matter) DDGS sources on diet composition

Ingredient, kg	High ME DDGS	Low ME DDGS
Corn	607.0	569.1
Soybean meal	172.5	172.5
High ME DDGS, 4,336 kcal/kg	200.0	
Low ME DDGS, 3,414 kcal/kg		200.0
Choice white grease		37.9
Limestone	10.0	10.0
Dicalcium phosphate	4.0	4.0
Salt	3.0	3.0
Vitamin/trace mineral premix	2.0	2.0
L-lysine HCl	1.5	1.5
TOTAL	1000.0	1000.0

Nutrient	High ME DDGS	Low ME DDGS
Dry matter %	87.39	84.03
Crude protein %	19.54	19.22
ME, kcal/kg	3526	3526
Lysine %	0.83	0.83
Methonine %	0.30	0.30
Threonine %	0.59	0.58
Tryptophan %	0.16	0.16
Calcium %	0.57	0.57
Total phosphorus %	0.52	0.51
Available phosphorus %	0.25	0.25
Ca:P	1.10	1.12

Table 2. Total and standardized ileal digestibility (SID) values for lysine, methionine, threonine, and tryptophan among three DDGS sources

Nutrient	Low SID Lysine	Average SID Lysine	High SID Lysine
ME, kcal/kg	3,834	3,893	3,838
Crude protein %	28.00	29.10	31.90
Lysine %	0.76	0.85	1.02
Methionine %	0.50	0.52	0.58
Threonine %	1.05	1.05	1.15
Tryptophan %	0.23	0.23	0.28
SID lysine %	0.47	0.60	0.67
SID methionine %	0.43	0.50	0.53
SID threonine %	0.79	0.80	0.87
SID tryptophan %	0.17	0.20	0.20

Table 3. Diet formulation of swine grower diets using low, average, and high standardized ileal digestibility (SID) lysine values for DDGS

Ingredient, kg	Low SID Lys. DDGS	Average SID Lys. DDGS	High SID Lys. DDGS
Corn	708.1	713.2	715.9
Soybean meal, 47 percent	172.7	167.5	164.8
DDGS	100.0	100.0	100.0
Dicalcium phosphate	3.0	3.1	3.2
Limestone	9.7	9.7	9.7
Salt	3.0	3.0	3.0
Vitamin/trace mineral premix	2.0	2.0	2.0
L-lysine HCL, kg	1.5	1.5	1.5
TOTAL	1,000	1,000	1,000
Nutrient Composition			
Crude protein %	17.03	16.94	17.11
ME, kcal/kg	3,416	3,422	3,416
Calcium %	0.50	0.50	0.50
Phosphorus %	0.45	0.45	0.45
Ca:P	1.11	1.11	1.11
Salt %	0.36	0.36	0.36
Crude fat %	4.34	4.26	4.24
Lysine %	0.90	0.90	0.91
SID lysine %	0.66	0.66	0.66
Methonine %	0.29	0.29	0.29
SID methonine %	0.26	0.26	0.26
Threonine %	0.63	0.62	0.63
SID threonine %	0.53	0.52	0.52
Tryptophan %	0.18	0.17	0.18
SID tryptophan %	0.15	0.15	0.15

content in the diets. Therefore, depending on the relative cost differences between corn, soybean meal, and DDGS, adding high SID lysine DDGS sources to swine diets generally reduces cost/ton of complete feed.

Impact of Formulation Methods on Diet Composition and DDGS Use in Swine Diets

Formulations on a crude protein basis

Several decades ago, swine diets in the U.S. were formulated on a crude protein basis because total and digestible amino acid requirements were not well established for different stages of production, and total and digestible amino acid content of feed ingredients had not been determined. However, once specific amino acid requirements were determined, nutritionists began formulating diets on a total amino acid basis, which improved accuracy of meeting the pig's requirements. Subsequent research showed that digestible amino acid content varied among ingredients and sources within ingredients. Numerous studies were then conducted to determine digestible amino acid requirements of pigs and the digestible amino acid content of ingredients to further improve precision swine nutrition. Today, the most accurate diet formulation method is to formulate swine diets on a standardized ileal digestible (SID) amino acid basis. Use of standardized ileal digestible amino acid content is more accurate than using apparent ileal digestible amino acid content because SID accounts for endogenous losses of amino acids, which are increased when feeding diets with relatively high fiber content. Use of SID amino acid content of DDGS will optimize the nutritional and economic value of swine diets as well as achieve optimal performance.

To show the potential problems that can occur when formulating swine DDGS diets on a crude protein basis, 3 diets were formulated to contain 0, 10 and 20 percent DDGS to meet the crude protein requirement (16 percent) of a 50 kg pig (Table 4). When the diet was formulated to maintain a constant crude protein level of 16 percent, the addition of 10 percent DDGS to the diet would meet all of the pigs' nutrient requirements, including amino acids. However, when the amount of DDGS in the diet is increased to 20 percent, it is impossible to meet the total lysine requirement of 0.75 percent for a 50 kg pig even though 0.15 percent of L-lysine HCl is added. If this diet was fed to pigs, growth rate and feed conversion would be reduced compared to feeding the 0 and 10 percent DDGS diets using this diet formulation approach.

Formulations on a total amino acid basis

To demonstrate the problems that can occur when formulating diets on a total amino acid basis for swine, four example DDGS diets (0, 10 percent, 20 percent and 20 percent with added synthetic amino acids) were formulated on a total amino acid basis to meet the nutrient requirements of a 50 kg pig (Table 5). Note that as dietary DDGS inclusion rates increased to 20 percent, the crude protein content also increased.

Although NRC requirements for total lysine, methionine, threonine, and tryptophan were met (and in some cases exceeded the requirements) in each of the diets, digestibility of the amino acids was not considered. As a result, the SID amino acid requirements for lysine and tryptophan were not met in either the 10 percent or 20 percent DDGS diets (Table 5). However, when the 20 percent DDGS diet was supplemented with synthetic L-tryptophan and more soybean meal (adjusted 20 percent DDGS), both the SID lysine and SID tryptophan requirements were met.

Formulations on a standardized ileal digestible (SID) amino acid basis

Currently, swine diets in the U.S. are formulated on a SID amino acid basis. This formulation method provides high accuracy in meeting the nutrient needs of pigs and allows nutritionists to use high dietary inclusion rates (up to 40 percent) of DDGS, if amino acid digestibility values are known for the source being fed, without compromising pig performance. As shown in Table 6, all diets formulated on a SID basis and containing up to 30 percent DDGS, meet the SID lysine content of 0.66 percent required for a 50 kg pig, and meet all other nutrient requirements including SID methionine, threonine, and tryptophan. Note that no additional synthetic amino acids were used in these diets beyond a constant inclusion rate of 0.15 percent L-lysine HCl. Greater dietary inclusion rates of DDGS can be achieved if supplemental synthetic threonine and tryptophan are added. These results show that in order to ensure excellent pig growth performance and carcass composition when adding DDGS up to 30 percent of the diet, diets must be formulated on a SID amino acid basis to meet the digestible amino acid requirements.

Use of synthetic amino acids and reduction in soybean meal use

Many growing-finishing swine DDGS diet formulations currently used in the U.S., include relatively high amounts of synthetic amino acids to replace a significant amount of soybean meal and increase the net energy content of the diet. Corn DDGS contains greater net energy content than soybean meal, and is often less expensive than both corn and soybean meal, which traditionally were the major energy and amino acid sources, respectively. However, diet must be formulated on a SID amino acid basis. The addition of synthetic (crystalline) amino acids to the diet has several advantages. First, it reduces excess nitrogen (protein) by reducing the amount of soybean meal or other high protein ingredients in the diet, while meeting the digestible amino acid requirements and optimizing growth performance. Secondly, use of synthetic amino acids minimizes nitrogen excretion and ammonia emissions from manure when feeding DDGS diets, which also significantly reduces total diet cost especially when soybean meal is expensive. Therefore, with increased commercial availability of crystalline lysine, methionine, threonine, and tryptophan at reasonable prices, a significant amount of soybean meal can be removed from the diet, while meeting the amino acid requirements.

An example diet was formulated to reduce the amount of soybean meal used in the 30 percent DDGS diet (Table 7). In this diet formulation, the amount of soybean meal provided was determined by using enough soybean meal to prevent the next (fifth) limiting amino acid (isoleucine) from becoming deficient. Diets were formulated on a SID amino acid basis to meet or exceed all NRC recommendations for 45 kg pigs. It is important to realize that one of the challenges of feeding diets containing high amounts (greater than 20 percent) of DDGS is the excessive amount of crude protein (nitrogen) it provides, due to its relatively high crude protein:lysine ratio. If the crude protein level in swine diets is too high, it can reduce growth performance because of the energetic cost of deamination and eliminating excess nitrogen from the pig's body. Therefore, by adding synthetic amino acid to DDGS diets, the amount of excess protein is reduced. In fact, by reducing soybean meal use to only 2 percent of the diet and adding enough synthetic amino acids to meet the pig's requirement, crude protein level was below a typical corn-soybean meal diet (Table 7).

Table 4. Ingredient and nutrient composition of a 16 percent crude protein swine grower diet containing 0, 10 and 20 percent DDGS

Ingredient, kg	0% DDGS	10% DDGS	20%t DDGS
Corn	783.5	733.8	684.2
Soybean meal, 47 percent	196.7	147.1	97.4
DDGS	0.0	100.0	200.0
Dicalcium phosphate	5.1	3.6	2.0
Limestone	8.2	9.0	9.9
Salt	3.0	3.0	3.0
L-lysine HCl	1.5	1.5	1.5
Vitamin/trace mineral premix	2.0	2.0	2.0
TOTAL	1000.0	1000.0	1000.0
Nutrient Composition			
Crude protein %	16.0	16.0	16.0
ME, kcal/kg	3,372	3,316	3,261
Lysine %	0.92	0.82	0.72
Methonine %	0.26	0.27	0.28
Threonine %	0.59	0.58	0.57
Tryptophan %	0.18	0.16	0.15
Calcium %	0.50	0.50	0.50
Phosphorus %	0.45	0.45	0.45
Ca:P	1.11	1.11	1.11
Salt %	0.37	0.41	0.44
Crude fat %	3.65	4.14	4.64

Table 5. Ingredient and nutrient composition of a swine grower diet containing 0, 10, and 20 percent DDGS and formulated on a total lysine basis

Ingredient, kg	0% DDGS	10% DDGS	20% DDGS	Adjusted 20% DDGS
Corn	796.5	757.5	635.4	610.9
Soybean meal, 47 percent	183.4	123.0	147.1	170.3
DDGS	0.0	100.0	200.0	200.0
Dicalcium phosphate	5.4	4.1	0.9	0.9
Limestone	8.1	9.0	10.0	9.9
Salt	3.0	3.0	3.0	3.0
Vitamin/Trace mineral premix	2.0	2.0	2.0	2.0
L-lysine HCl	1.5	1.5	1.5	1.5
L-tryptophan	0.0	0.0	0.0	1.5
TOTAL	1,000	1,000	1,000	1,000
Nutrient Composition				
Crude protein %	15.5	15.1	18.0	19.0
ME, kcal/kg	3,372	3,316	3,262	3,281
Lysine %	0.88	0.75	0.85	0.92
Methonine %	0.26	0.26	0.31	0.32
Threonine %	0.57	0.54	0.64	0.83
Tryptophan %	0.17	0.15	0.18	0.20
Calcium %	0.50	0.50	0.50	0.50
Phosphorus %	0.45	0.45	0.45	0.46
Ca:P	1.11	1.11	1.11	1.09
Salt %	0.37	0.41	0.44	0.44
Crude fat %	3.66	4.16	4.60	4.57
SID lysine %	0.66	0.52	0.60	0.66
SID methonine %	0.23	0.23	0.26	0.27
SID threonine %	0.49	0.44	0.51	0.54
SID tryptophan %	0.15	0.11	0.12	0.13

Table 6. Ingredient and nutrient composition of a swine grower diet containing 0, 10, 20 and 30 percent DDGS and formulated on a standardized ileal digestible (SID) lysine basis

Ingredient, kg	0% DDGS	10% DDGS	20% DDGS	30% DDGS
Corn	795.9	746.3	672.1	586.4
Soybean meal, 47 percent	184.0	134.4	109.8	96.6
DDGS	0.0	100.0	200.0	300.0
Dicalcium phosphate	5.4	3.9	1.7	0.0
Limestone	8.2	9.0	9.9	10.5
Salt	3.0	3.0	3.0	3.0
Vitamin/Trace mineral premix	2.0	2.0	2.0	2.0
L-lysine HCl	1.5	1.5	1.5	1.5
TOTAL	1,000	1,000	1,000	1,000
Nutrient Composition				
Crude protein %	15.48	17.17	18.86	20.55
ME, kcal/kg	3,371	3,317	3,262	3,205
Calcium %	0.50	0.50	0.50	0.50
Phosphorus %	0.45	0.45	0.45	0.49
Ca:P	1.11	1.11	1.11	1.02
Salt %	0.37	0.41	0.44	0.48
Crude fat %	3.66	4.54	4.58	5.04
Lysine %	0.88	0.90	0.92	0.94
SID lysine %	0.66	0.66	0.66	0.66
Methonine %	0.26	0.29	0.32	0.35
SID methonine %	0.23	0.25	0.27	0.29
Threonine %	0.57	0.63	0.68	0.74
SID threonine %	0.48	0.51	0.54	0.57
Tryptophan %	0.17	0.18	0.2	0.21
SID tryptophan %	0.15	0.14	0.13	0.12

Table 7. Ingredient and nutrient composition of a diet containing 30 percent DDGS, high amounts of synthetic amino acids and reduced soybean meal

Ingredient, kg	Control	Reduced Soybean Meal, 30% DDGS, and Synthetic Amino Acids
Corn	738.5	653.1
Soybean meal	238.8	20.0
DDGS	0.0	300.0
Limestone	8.2	12.0
Dicalcium phosphate	8.0	2.6
Salt	3.0	3.0
Premix	2.0	2.0
L-Lysine	1.5	5.9
L-Threonine	0.0	0.7
DL-Methionine	0.0	0.0
L-Tryptophan	0.0	0.7
TOTAL	1,000	1,000
Nutrient Composition		
Crude protein %	17.6	16.3
ME, kcal/kg	3,333	3,459
SID lysine %	0.92	0.84
SID methonine %	0.26	0.26
SID threonine %	0.56	0.52
SID tryptophan %	0.18	0.17
SID isoleucine. percent	0.61	0.46
Calcium %	0.60	0.58
Total phosphorus %	0.52	0.48
Available phosphorus %	0.21	0.26
Ca:P	1.15	1.20

Conclusions

In order to achieve the best economic and nutritional value from DDGS, the source, nutrient content and digestibility must be known. Depending on the nutrient composition of the DDGS source being used, and the diet formulation methods chosen, the relative economic and nutritional value of DDGS can vary substantially. Using accurate energy, amino acid and phosphorus digestibility values for DDGS can reduce excessive feeding of nutrients, avoid nutrient deficiencies and reduce diet costs while supporting optimal animal performance.

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CHAPTER 27

The Role of DDGS in Environmental Sustainability

Introduction

There are numerous research studies showing nutritional and economic benefits of using DDGS in animal feeds, but most nutritionists and animal producers are unaware of several environmental benefits that feeding DDGS can provide (Shurson, 2017). In recent years, environmental sustainability has become a new megatrend in agriculture around the world, and large multinational companies are beginning to source feed ingredients based not only on cost and nutritional value, but also on their environmental impact to reduce the overall carbon footprint of animal production systems. Kauffman (2015) described the characteristics of a low emission Chinese swine farm using a combination of nutrient, emission and waste management approaches. In China over four billion tons of manure is produced annually, much of which contributes to nutrient overloading in waterways and eutrophication and dead zones. As more land is converted to monocrop production of corn and soybeans, pesticides, herbicides and fertilizers pollute waterways, biodiversity declines, natural carbon sinks are destroyed due to direct and indirect land use change, and greenhouse gases are emitted in all stages of feed production and transport. As a result, Kaufmann (2015) recommended that the following practices be implemented to improve sustainable livestock production in China, but these practices can also be applied globally:

1. Determine the complete environmental costs of bioremediation of water, soil and air pollution including manure and agrochemical runoff and contamination as well as loss of livelihoods, costs associated with greenhouse gas emission and costs of loss of manure as a source of nutrients and organic matter for cropland and associated costs of using commercial fertilizers.

2. Exploit the full potential of reducing protein content in animal feeds by formulating swine and poultry diets based on standard ileal digestible amino acids, net energy and digestible or available phosphorus basis as well as use rumen protected amino acids for high performance lactating dairy cows.

3. Implement the use of methane digesters for biogas production and require large-scale commercial farms to build biogas facilities that use manure as the primary feedstock.

Food animal production contributes a portion (18 percent) of total greenhouse gas emissions (i.e. carbon dioxide, methane, nitrous oxide; Steinfeld et al., 2006) globally, which is primarily attributed to gastrointestinal fermentation of feed in animals and manure storage. Several multi-national integrated feed, animal production and food companies have begun implementing supply chain management strategies to reduce their carbon footprint by selecting feed ingredients that minimize the carbon footprint of food animal production. Furthermore, several researchers have begun conducting life cycle assessments of the environmental impacts of using various feed ingredients in animal feeds. However, the assumptions, breadth and scope of many of these assessments vary among studies and impact the results and their interpretation (Zilberman, 2017). In fact, many of the published studies do not include the economic impact of environmental assessments, use static instead of dynamic models and do not take into account the actual measured emission rates from feeding diets, which leads to misleading results.

In addition to increased global interest in reducing greenhouse gas emissions and the carbon footprint of animal agriculture, it is also essential to use precision animal feeding programs to improve caloric and nutritional efficiency of feeds to not only feed and production costs, but also reduce nutrient excretion in manure and reduce odor and gases from confinement animal facilities. Lu et al. (2017) summarized these major environmental concerns. High nitrogen, phosphorus and trace mineral concentrations in manure that is applied to cropland can cause soil concentrations of these nutrients to exceed crop removal rates. Nitrate can leach through soils and contaminate ground water supplies and is considered to be a major pollution concern on livestock and poultry farms. Methane and nitrous oxide produced in manure contribute to greenhouse gas emissions, and volatilization of ammonia causes acid rain that has detrimental effects on vegetation and trees. Furthermore, phosphorus can enter surface waters through soil erosion and increase growth of algae and other aquatic plants, which reduces dissolved oxygen that can cause fish death. In addition, soil accumulation of excessive trace minerals (e.g. copper and zinc) can increase the risk of toxicity of plants and microorganisms.

Lu et al. (2017) suggested several nutritional strategies that can be effective for minimizing excess nitrogen, phosphorus and trace mineral excretion in manure. First formulate diets to accurately meet dietary protein or amino acid, phosphorus and trace mineral requirements of animals. Dietary crude protein levels can be reduced by using supplemental synthetic amino acids or feed ingredients with high ruminally undegraded protein. Excess phosphorus excretion can be minimized by formulating swine and poultry diets on an available or digestible phosphorus basis and adding supplemental phytase. Using multiple phase-feeding programs to adjust diet formulations more frequently as nutrient requirements change during the various stages of production can substantially minimize excess nutrient excretion. Second, use high bioavailable sources of phosphorus and trace minerals and avoid excesses of these nutrients when formulating diets. Third, consider using effective feed additives such as enzymes, probiotics, prebiotics and others that improve nutrient utilization in animal feeds. By implementing all of these practices, it will not only reduce feed and production costs, but also minimize potential negative environmental impacts.

It is well documented that using crystalline amino acids and phytase in swine and broiler diets are effective for improving nutrient utilization efficiency, reducing diet cost, reducing nitrogen and phosphorus excretion in manure as well as emissions of gases such as ammonia. Kebreab et al. (2016) compared the impact of adding crystalline amino acids and phytase to swine and poultry diets without these supplements in Europe, North America and South America. Their results showed that using these supplements in pig and broiler diets reduced greenhouse gas emissions by 56 percent and 54 percent in Europe, 17 percent and 15 percent in North America and 33 percent and 19 percent in South America, respectively, compared with feeding diets without supplemental synthetic amino acids and phytase. These are substantial reductions and it is interesting to note that the North American swine and broiler diets used in this comparison contained 14.6 and 6.4 percent DDGS, respectively, but DDGS was not included in European and South American diets. As a result, the use of DDGS in animal feeds can be part of the solution for minimizing the negative environmental impacts of food animal production. This chapter summarizes several studies for various animal species that have shown beneficial effects of feeding DDGS on the environment.

Aquaculture

The global aquaculture industry continues to grow at a rapid pace, especially in Asian countries. For example, the aquaculture industry in Indonesia has increased 25 percent annually over the past five years (Henriksson et al., 2017a). As a result, significant attention is being directed toward methods to reduce its environmental impact and sustain long-term growth. One of the major factors that determine environmental impact in commercial aquaculture systems is the selection and use of feed ingredients. In fact, of all ingredients used in aquaculture systems, the use of fish meal has been the most criticized because of its negative environmental impacts and limitations for sustaining its widespread use in aqua feeds.

To compare the environmental impact of using common feed ingredients in aqua feeds in Indonesia, Henriksson et al. (2017a) classified them based on global warming, acidification, eutrophication, land occupation and fresh water consumption using life cycle assessment methodologies (Table 1). Shrimp meal had the greatest detrimental environmental impacts in all categories, while cassava had the least, except for land occupation of which fish oil had the least impact. Environmental impacts for corn flour and DDGS were generally intermediate among ingredients. When adding an economic allocation in the sensitivity analysis, there was minimal change in the allocation of environmental factors for cassava, corn flour, fish oil, wheat flour and corn gluten meal, but fish meal, rice bran, poultry by-product meal DDGS, corn gluten feed and shrimp meal had much lower impacts. The major reason for the reduction in most of these by-product ingredients is that the feed industry is utilizing these by-products that would otherwise be a waste stream in aqua feeds.

Tilapia farming has increased more than 20-fold over the past 20 years in Egypt and is the third largest animal production sector, providing 77 percent of the fish produced (El-Sayed et al., 2015; FAO, 2016). However, Egyptian fish farms are challenged with limited fresh water and achieving profitability. As a result, Worldfish implemented the "Improving Employment and Incomes through the Development of Egypt's Aquaculture Sector" project. This project provided training on best management practices and provided an improved strain of Nile tilapia to more than 500 fish farms. As a result, Henriksson et al. (2017b) conducted a benchmarking study to determine the environmental performance of using best management practices and genetic improvements in Egyptian aquaculture using life cycle assessment. Because Egypt is heavily dependent on imported feed ingredients, these researchers evaluated imported fish meal, fish oil, soybean meal, soybean oil and guar meal, along with poultry by-product meal rapeseed cake, corn gluten meal, corn gluten feed, corn flour, rice bran, wheat bran and DDGS. Based on their assumptions, the feed ingredients with the greatest contributions to global warming were soybean meal, wheat bran rice bran and corn gluten feed. However, on a per kilogram of ingredient basis, the ingredients with the greatest impact on greenhouse gas emissions were poultry by-product meal, fish meal, fish oil, corn flour, DDGS, corn gluten feed and corn gluten meal. However, the high impact of corn and corn co-products was caused by large dinitrogen monoxide emissions from Egyptian agricultural fields where excess nitrogen fertilizers are applied and suboptimal climatic conditions.

Beef and Dairy Cattle

Feeding high amounts of DDGS to dairy and beef cattle can result in increased nitrogen (N) and phosphorus (P) excretion in manure because DDGS contains about three times the crude protein and phosphorus content compared with corn.

Table 1. Comparison of feed ingredients used in the commercial aquaculture industry in Indonesia on their relative environmental impacts[1] (adapted from Henriksson et al, 2017[a])

Ingredient	Global warming[2]	Eutrophication[3]	Acidification[4]	Land occupation[5]	Fresh water consumption[6]
Fish meal	H	M	M	L	L
Shrimp meal	H*	H*	H*	H*	H*
Poultry by-product meal	H	H	H	H	M
Soybean meal	M	L	L	M	M
Corn gluten meal	H	M	H	M	M
Corn gluten feed	H	M	H	M	M
DDGS	M	M	M	M	M
Cassava	L**	L**	L**	M	L**
Corn flour	L	M	M	M	M
Wheat flour	M	M	M	M	M
Wheat bran	M	M	M	M	M
Rice bran	L	H	L	M	H
Fish oil	L	M	L	L*	L
Soybean oil	L	L	L	M	M

[1] H = high; M = medium; L = low

[2] Global warming = greenhouse gas emissions/ton

[3] Eutrophication = phosphorus and nitrogen runoff potential/ton

[4] Acidification = sulfur dioxide and nitrogen oxide emissions/ton

[5] Land occupation = land resources required/ton produced

[6] Fresh water consumption = cubic meters of water required/ton produced

*Highest impact among ingredients

**Lowest impact among ingredients

Nitrogen and phosphorus use efficiency can be improved by increasing N and phosphorus retention, reducing excess N and phosphorus intake, or both. Supplementing cattle on pasture with DDGS can result in N fertilization because DDGS contains a relatively high concentration of crude protein (N), and excess N is excreted as urea in urine. However, when manure is properly managed and applied to cropland, it serves as a very valuable fertilizer for crop production. In addition, for cattle grazing pastures, greater N content in urine has been shown to significant increase grass forage production when applied to actively growing grasses (Ball and Ryden, 1984).

Nitrogen and phosphorus utilization efficiency

Greenquist et al. (2011) compared the effects of N fertilization of smooth bromegrass pasture with providing supplemental DDGS to yearling steers on smooth bromegrass pasture on N utilization efficiency of the whole system. Nitrogen retention per hectare was 30 and 98 percent greater supplemented with 2.3 kg of DDGS per steer daily compared with those on pasture fertilized with 90 kg of N/hectare and steers grazing bromegrass pasture that was not fertilized and no supplemental DDGS was provided. Nitrogen excretion was also greater for DDGS supplemented steers than those grazing fertilized bromegrass, and both grazing systems resulted in more N excretion than the control. Although animal N utilization efficiency was not different among grazing treatments, N utilization efficiency improved 144 percent when supplementing grazing cattle with DDGS compared with fertilized bromegrass pasture, which indicates that feeding DDGS can improve N utilization efficiency of the whole bromegrass grazing system.

Bernier et al. (2014) evaluated N and phosphorus utilization of beef cows fed poor quality forage with or without protein provided by a 50:50 blend of corn and wheat DDGS when exposed to thermal neutral and prolonged cold climate conditions. Feeding DDGS increased total N and phosphorus content of manure, as well as the chemical forms of N and phosphorus that have the potential to increase nutrient runoff when manure is applied to cropland. However, results from this study showed that cows exposed to cold conditions have different protein and phosphorus requirements and utilization than cows exposed to thermal neutral conditions.

Hao et al. (2011) determined the effects of adding condensed tannins to cattle diets containing corn DDGS, and using open windrow manure composting, on nitrogen content and greenhouse gas emissions from manure composting. Concentrations of total carbon, nitrogen and ammonia in the final compost were greater in manure from cattle fed 40 percent DDGS diets with 2.5 percent condensed tannins than for composted manure from cattle fed only DDGS or the control diet. Adding condensed tannins had no effect on carbon dioxide, methane or nitrous oxide emissions during composting. These results showed that feeding diets containing 40 percent DDGS and condensed tannins increase the fertilizer value of manure compost without increasing greenhouse gas emissions.

Methane emissions

Cropland and pasture used for food, fiber, and biofuels production emits about 13.5 percent of greenhouse gases globally, and agricultural activities account for about 85 percent of nitrous oxide and 50 percent of methane emissions, which comprise 70 percent of non-carbon dioxide emissions from agriculture (IPCC, 2007). Emissions of carbon dioxide, methane and nitrous oxide into the atmosphere have been increasing over the past several decades and have been considered to be a major cause of climate change. The increase in carbon dioxide emissions have been primarily attributed to burning of fossil fuels, but significant quantities of methane and nitrous oxide emissions are produced in agriculture (Smith et al., 2007). While most of the nitrous oxide emissions are derived from soil (resulting from fertilizer and manure), most of the methane produced is derived from gastrointestinal fermentation in livestock. Therefore, there is tremendous interest and need to implement feeding, housing and management practices to mitigate emissions of methane in livestock production systems (Beauchemin et al., 2011).

Ruminants are a major contributor to methane emissions. Hristov et al. (2014) reviewed various strategies to mitigate enteric methane emissions in livestock operations. Although the effects of feeding corn DDGS on methane emissions are inconsistent among species, emissions in ruminants can be reduced by feeding reduced-oil DDGS (Hristov et al., 2014), because dietary lipid content appears to affect methane emissions (Hunerberg et al., 2013). Hristov et al. (2014) suggested that increasing forage digestibility and digestible forage intake is one of the major strategies to reduce methane emissions in ruminants. They also suggested that supplementing ruminant diets with feed ingredients containing relatively high lipid content (i.e. DDGS) can significantly reduce methane emissions. In fact, several studies have shown that methane emissions in beef and dairy cattle are reduced when feeding diets containing DDGS.

Drehmel et al. (2016) showed that the addition of corn oil to neutral detergent fiber residues derived from DDGS reduced production of methane while adding cellulose to DDGS increased methane production using an in vitro gas production technique, which suggests that manipulating dietary components can be used to reduce methane emissions in ruminants. McGinn et al. (2009) reported that methane emissions were reduced by 16 to 24 percent when 35 percent DDGS replaced barley in a beef cattle backgrounding diet when additional 3 percent lipid was added to dry matter. Feeding corn DDGS to feedlot cattle reduced methane emissions compared with feeding wheat DDGS and control diets (Hunerberg et al., 2013). However, when DDGS is used as an energy source and fed at high dietary inclusion rates to beef feedlot cattle, cattle consume excess protein (nitrogen) which dramatically increases nitrogen excretion in manure (Hunerberg et al., 2013).

Feeding DDGS to dairy cows has also been shown to reduce enteric methane emissions while increasing the bioenergy potential (methane production) from anaerobic digestion of manure (Masse et al., 2014). Benchaar et al. (2013) evaluated the effects of replacing corn and soybean meal with 0, 10, 20 or 30 percent high-oil DDGS in lactating dairy cow diets on enteric methane emissions and ruminal fermentation characteristics of dairy cows. Increasing dietary DDGS levels increased dry matter intake and milk yield, and methane production decreased linearly (Table 2). The reduction in methane production was attributed to increased amounts of lipid provided by DDGS and its effects on rumen fiber degradation, acetate:propionate and protozoa numbers. Results from this study indicate that feeding reduced-oil DDGS to lactating dairy cows is effective in reducing methane emissions while also improving dry matter intake and milk yield.

Table 2. Effects of feeding increasing levels of reduced-oil DDGS to lactating dairy cows on dry matter intake, milk yield, rumen pH and protozoa, and methane production (adapted from Benchaar et al., 2013)

Measure	0% DDGS	10% DDGS	20% DDGS	30% DDGS
Dry matter intake, kg/day	24.2	24.6	24.4	25.3
Milk yield, kg/day	32.6	35.1	35.8	36.6
Energy-corrected milk yield, kg/day[1]	35.3	37.8	37.3	37.1
4% fat-corrected milk, kg/day[2]	32.1	34.5	34.1	33.7
Milk/dry matter intake	1.40	1.44	1.44	1.45
Energy-corrected milk/dry matter intake	1.51	1.55	1.50	1.46
Rumen pH				
Minimum	5.92	5.92	5.98	5.97
Maximum	6.56	6.59	6.64	6.55
Average	6.21	6.21	6.27	6.22
Protozoa ($\times 10^5$/mL)	5.12	5.28	5.42	4.48
Methane production				
g/day	495	490	477	475
g/kg dry matter intake	0.6	20.1	19.7	18.9
% of gross energy intake	6.09	5.80	5.61	5.23
% of digestible energy intake	8.75	8.39	8.17	7.74
g/kg milk	15.6	14.2	13.6	13.2
g/kg fat-corrected milk	15.7	14.3	14.3	14.4
g/kg energy-corrected milk	14.3	13.1	13.0	13.0
g/kg milk fat	396	363	372	390
g/kg milk protein	446	415	411	400

[1] Energy-corrected milk = 0.327 × milk yield (kg/day) + 12.95 × milk fat yield (kg/day) + 7.2 × protein yield (kg/day)

[2] 4 percent fat-corrected milk = 0.4 × milk yield (kg/day) + 15 × milk fat yield (kg/day)

Judy et al. (2016) conducted a study with lactating dairy cows to determine the effects of feeding 20 percent reduced-oil DDGS diets, with or without 1.4 percent added corn oil, and a 20 percent reduced-oil DDGS diet with 0.93 percent added calcium sulfate on methane emissions. Feeding the reduced-oil DDGS diet increased dry matter intake and milk yield compared with feeding the control diet with no DDGS. Feeding the 20 percent reduced-oil DDGS diet had no effect on methane emissions compared with the control diet. However, adding calcium sulfate to the 20 percent DDGS diet reduced total methane produced compared with cows fed the control diet, and adding corn oil to the reduced-oil DDGS diet tended to reduce methane production. Similarly, when methane production was expressed as per unit of fat-corrected milk or per unit of dry matter intake, adding calcium sulfate or corn oil to the reduced oil DDGS diet reduced methane production compared with cows fed the control diet. These results show that adding calcium sulfate or corn oil to reduced-oil DDGS diets is effective in reducing methane emissions without affecting milk production.

Hydrogen sulfide emissions

Feeding diets containing high amounts of sulfur (greater than 0.40 percent) can potentially be toxic to ruminants, and although sulfur content in DDGS is variable, some sources contain relatively high concentrations. In addition, dietary sulfur can contribute to hydrogen sulfide emissions from the rumen and manure, and can cause sudden death in animals and humans if it is present in the production facilities at high concentrations. Drewnoski et al. (2014) conducted a study to compare hydrogen sulfide emissions from feeding 42 percent DDGS (contributed 0.40 percent sulfur to the diet), 7 percent dry matter of corn condensed distillers solubles (contributed 0.19 percent sulfur to the diet), and diets containing 21 percent DDGS (contributed 0.19 percent sulfur to the diet) with either supplemental sulfuric acid, sodium sulfate or calcium sulfate contributing 0.17 percent of total sulfure to the diets. Results from this study showed that there was no difference in sulfur intake or ruminal hydrogen sulfide concentration among dietary treatments suggesting that there was no difference in toxicity or hydrogen sulfide concentrations in the rumen. In a subsequent study, Morine et al. (2014) fed steers diets containing increasing amounts of forage to provide increasing dietary levels of neutral detergent fiber from bromegrass hay, and DDGS and condensed distillers solubles providing 0.46 percent sulfur to the diet, on rumen hydrogen sulfide concentrations. Results from this study showed that increasing the amount of NDF supplied by forage in the diet helped maintain high ruminal pH and decreased hydrogen sulfide concentration. Using this diet formulation strategy may be effective in not only reducing the risk of sulfur toxicity when feeding high sulfur diets, but also reduce hydrogen sulfide emissions.

Biogas production for energy use

Aguirre-Villegas et al. (2015) evaluated the effects of supplementing nutritionally balanced lactating dairy cow rations with varying amounts of DDGS, soybean meal and forage types, and integrating dairy and bioenergy production systems (manure anaerobic digesters) on land use, net energy intensity and greenhouse gas emissions. Within the integrated dairy and manure anaerobic digester system, maximizing the use of DDGS in the diets resulted in the greatest reduction in greenhouse gas emissions and net energy intensity, but increased land use compared to the reference system. These results indicated that implementing the use of anaerobic digesters on dairy farms can result in a 65 percent reduction in net energy intensity and reduce greenhouse gas emissions by 77 percent. Therefore, feeding DDGS diets has a significant positive impact on reducing energy use and greenhouse gas emissions on dairy farms using anaerobic digesters.

Poultry

Poultry manure contains significant nitrogen content, which if not properly managed can cause nitrate or nitrite contamination of water supplies, eutrophication, ammonia volatilization and increased nitrous oxide emissions. If diets contain excess protein above the bird's requirement, it is excreted as uric acid in manure where it is converted to ammonia by manure microbes (Pineda et al., 2008).

Nitrogen and phosphorus utilization efficiency

Feeding increasing dietary levels (up to 20 percent) of DDGS to broilers had no effect on dry matter and N excretion, but reduced P excretion when diets were formulated on a digestible amino acid basis and available phosphorus basis (Deniz et al., 2013). Similarly, Abd El-Hack and Mahgoub (2015) showed that N excretion in manure decreased by 8.6 and 4.3 percent in laying hens fed 5 or 10 percent DDGS diets, respectively, and phosphorus excretion was reduced by 3.3, 7.2 and 10.6 percent in laying hens fed 5, 10 or 15 percent DDGS diets compared with hens fed the control diet.

Martinez-Amezcua et al. (2006) conducted three experiments to evaluate the effectiveness of adding OptiPhos® phytase and citric acid to broiler diets for improving phosphorus availability in DDGS. In one of the experiments, they used a slope-ratio chick growth and tibia ash assay and determined that the bioavailability of phosphorus in DDGS was 67 percent. In another experiment, supplemental phytatse and citric acid released from 0.04 to 0.07 percent more phosphorus from DDGS, which suggests that both OptiPhos® phytase and citric acid supplementation can be used to increase the availability of phosphorus in DDGS for poultry. Therefore, the use of supplemental phytase and citric acid can increase the bioavailability of phosphorus in DDGS from 62 to 72 percent and reduce P excretion in poultry manure. Furthermore, Masa'deh (2011) reported that phosphorus excretion decreased linearly as dietary DDGS content increased.

Ammonia and hydrogen sulfide emissions

Feeding 20 percent DDGS diets to laying hens reduced emissions of ammonia by 24 percent and hydrogen sulfide by 58 percent compared to feeding a corn-soybean meal diet, with no effect on egg production and egg quality (Wu-Haan et al., 2010). The reduction in ammonia observed in this study is consistent with results reported by Roberts et al. (2007) and Li et al. (2012). This was confirmed in a subsequent study conducted by Li et al. (2014) which showed that feeding DDGS diets to laying hens decreased ammonia, but increased methane emissions without affecting other gases (Li et al., 2014). The reduction in hydrogen sulfide emissions reported by Wu-Haan et al. (2010) occurred despite greater sulfide concentrations in the litter and manure crusting was not reported. Undigested fiber in DDGS is fermented in the lower gastrointestinal tract of birds, resulting in the production of short chain fatty acids, which can reduce the pH of manure. Manure with low pH reduces the production of ammonium, which is non-volatile form of N, resulting in a less harmful effect on air quality (Babcock et al., 2008; Bregendahl et al., 2008). Therefore feeding DDGS not only reduces ammonia emissions, but it also increases the amount of N present in manure which increases its fertilizer value when applied to cropland. The fertilizer value of manure from an 800,000 laying hen operation fed 16 percent DDGS diets compared with no DDGS increased by $5,000/year on a N basis, and $47,000/year on a four-year P basis (Regassa et al., 2008)

Results from these studies indicate that feeding DDGS diets to layers and broilers can have a significant impact on reducing N and phosphorus excretion in manure, as well as reducing ammonia and hydrogen sulfide emissions.

Swine

Swine diets containing DDGS contain higher fiber, crude protein and sulfur compared to traditional corn-soybean meal diets (Kerr et al., 2008; Zhang, 2010), which affects nutrient digestibility and excretion (Kerr et al., 2003; Degen et al., 2007; Kil et al., 2010; Anderson et al., 2012). Due to the relatively high fiber content of DDGS, dry matter excretion is increased when feeding DDGS compared to corn-soybean meal diets without DDGS (Almeida and Stein, 2012). This results in increased manure volume produced, which may increase the need for greater manure storage capacity or more frequent manure removal from swine production facilities.

Nitrogen and phosphorus utilization efficiency

McDonnell et al. (2011) evaluated the effects of adding 0, 10, 20 or 30 percent corn DDGS to replace wheat in wheat and barley based diets, formulated on a net energy, ileal digestible amino acid, and digestible phosphorus basis, on N and phosphorus balance of growing-finishing pigs. As expected, N intake and urinary and total N excretion linearly increased with increasing DDGS levels in the diets (Table 3). This was due to feeding excess N from DDGS relative to pig requirements, resulting in increased deamination of excess amino acids and increased urinary excretion. Nitrogen retention was not affected by feeding the 10 and 20 percent DDGS diets, but feeding the 30 percent DDGS diet decreased N retention relative to nitrogen intake. The increased N excretion commonly observed by feeding DDGS diets to swine can be minimized by using synthetic amino acids to reduce the amount of excess protein (N) in the diet. In contrast, phosphorus intake linearly increased with increasing dietary DDGS levels, but there was no effect on P excretion or retention. These results indicate that feeding diets containing up to 30 percent DDGS increases N excretion but has no effect on phosphorus excretion in growing-finishing pigs when diets are formulated on a digestible amino acid and phosphorus basis.

Baker et al. (2013) compared the phosphorus balance and digestibility between dicalcium phosphate and DDGS for growing pigs and showed that although the standardized total tract digestibility of phosphorus from DDGS was less than dicalcium phosphate, it was quite high (93.1 and 63.1 percent, respectively), and did result in greater fecal excretion than dicalcium phosphate (Table 4). However, dicalcium phosphate is a much more expensive source of phosphorus in animal feeds and global supplies of inorganic phosphate reserves are rapidly declining, which makes DDGS an excellent and more sustainable alternative phosphorus source in swine diets.

Table 3. Effects of adding increasing levels of corn DDGS to wheat and barley based diets on nitrogen and phosphorus balance in growing-finishing pigs (McDonnell et al., 2011)

Measure	0% DDGS	10% DDGS	20% DDGS	30% DDGS
Nitrogen, g/day				
Intake[1]	52.7	57.2	57.9	62.8
Fecal excretion	7.3	6.2	7.4	8.0
Urine excretion[1]	15.0	18.0	17.2	20.8
Total excretion[1]	22.3	24.2	24.6	28.7
Retention	30.5	33.0	33.3	34.1
Retained/Intake[2]	0.58	0.58	0.58	0.54
Phosphorus, g/day				
Intake	9.7	9.6	9.1	8.9
Fecal excertion	3.7	3.7	3.3	3.3
Urine excretion	0.69	0.56	0.62	0.94
Total excretion	4.4	4.3	3.1	4.2
Retention	5.3	5.3	5.0	4.7

[1] Linear increase to increasing dietary DDGS levels (P less than 0.01)

[2] Quadratic response to increasing dietary DDGS levels (P less than 0.05)

Table 4. Comparison of phosphorus intake, excretion and digestibility between dicalcium phosphate and DDGS (adapted from Baker et al., 2013)

Measure	Dicalcium phosphate	DDGS
Feed intake, g/day	1,023	925
Phosphorus intake, g/day	2.5	3.8
Fecal phosphorus excretion, g/day	0.3	1.6
Apparent total tract digestibility of phosphorus %	86.1	58.5
Standardized total tract digestibility of phosphorus %	93.1	63.1

The addition of microbial phytase to swine diets has become a common practice to improve phosphorus digestibility, reduce phosphorus excretion in manure, and reduce diet cost by reducing the amount of inorganic phosphate required in the diet. Almeida and Stein (2012) added increasing levels of microbial phytase (0, 500, 1,000 or 1,599 phytase units) to corn or 50 percent DDGS diets and showed a linear improvement in standardized total tract digestibility of phosphorus in corn (40.9, 67.5, 64.5 and 74.9 percent, respectively), and tended to increase phosphorus digestibility in DDGS (76.9, 82.9, 82.5 and 83.0 percent, respectively). However, the magnitude of improvement in phosphorus digestibility by adding phytase to DDGS diets was much less than observed for corn and may not justify the additional cost of adding high amounts of phytase to swine diets.

Rojas et al. (2013) compared the phosphorus balance and digestibility of corn, DDGS and corn gluten meal, with and without 600 FTU/kg diet of supplemental phytase, when fed to growing pigs. Total phosphorus excretion was greatest for pigs fed the corn diet without phytase supplementation but was reduced by 50 percent when phytase was added (Table 5). However, feeding DDGS without phytase resulted in 40 percent less phosphorus excretion than feeding corn without phytase, and feeding corn gluten meal without phytase resulted in a 60 percent reduction in phosphorus excretion compared to feeding corn. Adding phytase to the corn diet had the greatest magnitude of improvement on reducing phosphorus excretion, with no benefit in the DDGS diets, and some improvement when phyatse was added to the corn gluten meal diet. As a result, adding phytase to corn and corn gluten meal diets improves standardized total tract digestibility of corn and corn gluten meal, but not DDGS. This lack of response to adding phytase to DDGS diets is a result of the already high phosphorus digestibility that occurs from the degradation of phytate during the fermentation process in dry-grind ethanol plants. Therefore, formulating DDGS diets on a digestible phosphorus basis for swine can dramatically reduce phosphorus excretion in manure compared with feeding corn based diets.

Table 5. Effect of microbial phytase supplementation (600 phytase units/kg) on fecal phosphorus concentration, excretion, and digestibility of corn, DDGS, and corn gluten meal (adapted from Rojas et al., 2013)

Measure	Corn		DDGS		Corn gluten meal	
	- Phytase	+ Phytase	- Phytase	+ Phytase	- Phytase	+ Phytase
Feed intake, g dry matter/day	481	456	463	471	475	482
P intake, g/day	1.6^{b}	1.1^{c}	2.2^{a}	2.2^{a}	1.0^{c}	1.0^{c}
P in feces %	2.0^{b}	1.1^{d}	0.9^{de}	0.7^{e}	2.4^{a}	1.4^{c}
P excretion, g/day	1.0^{a}	0.5^{c}	0.6^{bc}	0.5^{c}	0.4^{c}	0.2^{d}
Apparent total tract digestibility of phosphorus %	36.4^{d}	56.1^{c}	72.2^{ab}	78.5^{a}	70.6^{ab}	77.6^{a}
Standardized total tract digestibility of phosphorus %	42.5^{d}	64.1^{c}	76.5^{b}	82.8^{ab}	75.2^{b}	87.4^{a}

^{a,b,c,d,e}Means with different superscripts within row are different (P less than 0.05)

Feeding high fiber diets to ruminants and monogastric animals has been shown to increase the production of methane (Jarret et al., 2011; Klevenhusen et al., 2011). Furthermore, feeding diets containing DDGS may increase sulfur content which may cause an increase in hydrogen sulfide and other reduced-sulfur compounds and increase odor of swine manure (Blanes-Vidal et al., 2009; Feilberg et al., 2010; Trabue et al., 2011). Furthermore, the relatively high protein content relative to lysine content in DDGS results in increased protein and nitrogen content in animal feeds which can lead to increased nitrogen excretion and potentially ammonia production. Ammonia and hydrogen sulfide are two of the major gases produced from swine manure during storage.

Ammonia, hydrogen sulfide, methane and odor emissions

Several studies have been conducted to determine the effects of feeding DDGS to swine on gas and odor emissions from manure. Powers et al. (2009) measured air emissions of ammonia, hydrogen sulfide, methane and non-methane hydrocarbons when feeding diets containing 0 or 20 percent DDGS to growing-finishing pigs, with either supplemental inorganic or organic trace minerals. Although feeding the organic trace mineral sources reduced the increased hydrogen sulfide emissions resulting from feeding the 20 percent DDGS diet, ammonia, methane and non-methane hydrocarbon emission increased when feeding the DDGS diet. This is the only study that has shown an increase in ammonia and hydrogen sulfide emissions from feeding DDGS diets to pigs. Spiehs et al. (2012) observed no differences when feeding a 20 percent DDGS diet compared with a corn-soybean meal diet to growing pigs over a 10-week feeding period on total reduced sulfur, ammonia or odor concentrations.

Trabue et al. (2016) fed growing pigs diets containing 35 percent DDGS over a 42-day period and observed a reduction in manure pH and increased manure surface crust coverage, dry matter content, as well as increased concentrations of carbon, nitrogen and sulfur in manure compared with pigs fed a corn-soybean meal diet (Table 6). Warmer temperatures are often observed for manure with greater surface crusting or foam (van Weelden et al., 2015), and is associated with animals fed high fiber diets (Misselbrook et al., 2005; Lynch et al., 2007; Wood et al., 2012) and lower pH (Kerr et al., 2006). As a result, the increased crusting of manure (Wood et al. 2012), temperature (Blunden and Aneja, 2008; Blunden et al., 2008; Rumsey and Aneja, 2014) and reduced pH associated with feeding DDGS diets can reduce gas emissions. In fact, ammonia and hydrogen sulfide emissions from manure produced by pigs fed DDGS was less than from those fed a corn-soybean meal diet, but volatile fatty acid and phenolic compound concentrations were greater in manure from pigs fed the DDGS diet (Table 6). It is likely that the increased crusting of manure from pigs fed the DDGS diet reduced hydrogen sulfide emissions by acting as a barrier for emission to the air.

The emissions of various odor compounds from manure in the study conducted by Trabue et al. (2016) are shown in Table 7. These data were normalized for pig weight (animal unit) and nutrients consumed. Pigs fed the corn-soybean meal diet had greater ammonia (53 percent of N consumed) and hydrogen sulfide emissions (9 percent of sulfur consumed) than pigs fed the 35 percent DDGS diet (30 percent of N consumed and 2 percent of S consumed). These results are consistent with those from other studies where ammonia emissions were reduced from feeding DDGS diets to swine (Li et al., 2011) and poultry (Roberts et al., 2007; Wu-Haan et al., 2010; Li et al., 2012), which is likely due to reduced pH of manure (Roberts et al., 2007) and increased microbial activity from more carbon present in manure (Kerr et al, 2006; Ziemer et al., 2009). However, manure from pigs fed the 35 percent DDGS diet had greater volatile fatty acid and phenolic compound emissions, but no difference in indole emission than manure from pigs fed the corn-soybean meal diet (Table 7). These differences were relatively small compared with ammonia and hydrogen sulfide emissions because total volatile organic compound emissions represented less than 1 percent of the total carbon consumed from feeding both diets. Human panelists detected no differences in odor of compounds emitted from manure from pigs fed the two diets, but chemical analysis of individual odorous compounds showed greater hydrogen sulfide and ammonia, and less total volatile fatty acids and phenols in manure emissions from pigs fed the corn-soybean meal diet than those fed the DDGS diet. The majority (60 percent) of odorous compounds in swine manure were derived from ammonia and hydrogen sulfide. These data indicate that controlling nitrogen and sulfur excretion when feeding DDGS diets does not change ammonia and hydrogen sulfide emissions because the sulfur content in the DDGS diet was almost twice as high as in the corn-soybean meal diet (Trabue and Kerr, 2016), but manure hydrogen sulfide emissions from manure of pigs fed the DDGS diet was about 30 percent less than those fed the corn-soybean meal diet.

Table 6. Manure characteristics and air concentrations of odorous compounds from pigs fed corn-soybean meal and 35 percent DDGS diets (adapted from Trabue et al., 2016)

Measurement	Corn-soybean meal diet	35% DDGS diet
Manure characteristics		
Temperature, °C	14.1^b	14.5^a
Dry matter %	3.4^b	6.2^a
Crusting %	16.7^b	87.5^a
pH	8.42^a	7.61^b
Total ammoniacal nitrogen, µmol/g	480^b	628^a
Total sulfide sulfur, µmol/g	0.41^b	0.79^a
Air odorant concentrations, µg/m^3		
Ammonia	12,627^a	8,651^b
Hydrogen sulfide	189^a	129^b
Acetic acid	0.2^{9}b	21.3^a
Propanoic acid	0.50^b	20.0^a
2-methyl propanoic acid	0.49^b	17.9^a
Butanoic acid	0.67^b	32.1^a
3-methyl butanoic acid	0.36^b	17.7^a
Sum of volatile fatty acids ($C_5 – C_7$)	0.23	8.1
Phenol	33.3^b	54.6^a
4-methylphenol	12.4^b	24.1^a
4-ethylphenol	7.7^b	2.6^a
Indole	0.48	0.78
3-methylindole	1.06	0.57

^{a,b}Means with different superscripts within row are different (P less than 0.05)

Table 7. Emissions of odorous compounds from stored swine manure for pigs fed corn-soybean meal and 35 percent DDGS diets (adapted from Trabue et al., 2016)

Gas emission factor	Corn-soybean meal diet	35% DDGS diet
Ammonia, kg NH_3/day/animal unit	185.9[a]	112.4[b]
Ammonia, g N/kg N consumed	528.7[a]	289.3[b]
Hydrogen sulfide, kg H_2S/day/animal unit	1.80[a]	0.87[b]
Hydrogen sulfide, g S/kg S consumed	90.6[a]	22.7[b]
Total volatile fatty acids, mg VFA/day/animal unit	14.0[b]	1,752[a]
Total phenols, mg phenols/day/animal unit	554[b]	960[a]
Total indoles, mg indoles/day/animal unit	21.9	19.1
Total volatile organic compounds, g C/kg C consumed	0.31[b]	0.74[a]
Human odor panel[2]	772	700
Hydrogen sulfide[3]	576[a]	287[b]
Ammonia[3]	40.1[a]	27.6[b]
Total volatile fatty acids[3]	4.7[b]	484[a]
Total phenols[3]	212[b]	485[a]
Total indoles[3]	114	58
Total odor activity value[3]	862	948

[1] Animal unit = 500 kg body weight

[2] Values based on dilution thresholds and chemical analysis reported in odor activity values

[3] Values measured by human panels and chemical analysis normalized for live animal weight of 500 kg

[a,b] Means with different superscripts within row are different (P less than 0.05)

Carbon dioxide, methane and nitrous oxide are major greenhouse gases of concern in animal production systems. From the same study (Trabue et al., 2016), emissions of the major carbon, nitrogen and sulfur gasses were also determined (Trabue and Kerr, 2016). Results from this study showed that carbon dioxide, methane, and nitrous oxide emissions, expressed on an animal unit and amount of element consumed basis, were not different between the two diets (Table 8). However, as previously described, ammonia and hydrogen sulfide emission were reduced by feeding the DDGS diet. These results show that pigs fed DDGS diets have no greater greenhouse gas emissions from stored manure than those fed corn-soybean meal diets.

Manure foaming

In 2009, foaming manure became a widespread problem in the pork industry in the United States, causing decreased storage capacity in anaerobic manure pits and increased production of biogases, which created human and animal safety concerns. Although feeding DDGS diets was suggested as a potential contributing factor to this phenomenon, studies (Luo et al., 2015; van Weelden et al., 2016) have shown no direct evidence that feeding DDGS diets increases manure foaming. Results from these studies showed that foaming properties of manure were increased by larger particle size of feed and greater dietary fiber content, which reduce nutrient digestibility and increase dry matter excretion. Furthermore, Van Weelden et al. (2016) showed that manure from pigs fed coarse ground diets containing corn and soybean meal had the lowest methane production rate, and those fed corn-soybean meal-soybean hulls diets had the greatest methane production, with manure from pigs fed the 35 percent DDGS diet having an intermediate methane production rate. However, the biochemical methane production potential was greatest when feeding the 35 percent DDGS diet compared with corn-soybean meal or corn-soybean meal-soybean hulls diets. This suggests that for swine farms installing biogas production systems to capture energy from manure, feeding DDGS diets would provide manure with high amounts of carbon to generate higher amounts of methane.

Life cycle assessment

There is increasing interest in conducting life cycle assessments of the environmental impacts of using various feed ingredients in the swine industry. Lammers et al. (2010) conducted a partial life cycle assessment, which only included production and processing of feed ingredients used in Iowa swine diet formulations, including DDGS, and focused on non-solar energy use and global warming

Table 8. Emissions of major carbon, nitrogen, and sulfur gases in stored swine manure for pigs fed corn-soybean meal and 35 percent DDGS diets (adapted from Trabue and Kerr, 2016)

Gas emission factor	Corn-soybean meal diet	35% DDGS diet
Carbon dioxide, kg CO_2/day/animal unit[1]	3.89	3.71
Carbon dioxide, g C/kg C consumed	285.6	252.5
Methane, kg CH_4/day/animal unit	18.5	21.9
Methane, g C/kg C consumed	5.2	5.6
Ammonia, kg NH_3/day/animal unit	185.9[a]	112.4[b]
Ammonia, g N/kg N consumed	528.7[a]	289.3[b]
Nitrous oxide, kg N_2O/day/animal unit	7.9	7.5
Nitrous oxide, g N/kg N consumed	20.7	19.0
Hydrogen sulfide, kg H_2S/day/animal unit	1.80[a]	0.87[b]
Hydrogen sulfide, g S/kg S consumed	90.6[a]	22.7[b]

[1] Animal unit = 500 kg body weight

[a,b] Means with different superscripts within row are different (P less than 0.05)

potential. Unfortunately, economic analyses of diets were not considered in this study which provided misleading results. In another study by Thoma et al. (2011), there was about a 6 percent increase in the overall carbon footprint of pork production (production to consumption) when DDGS was included in swine diets, which was attributed to the additional energy consumed during processing of corn during the ethanol and co-product production process compared with corn grain and soybean meal.

The environmental impacts of using co-products from human food and biofuels supply chains in pig diets in Canadian pork production systems were determined in a life cycle assessment by Mackenzie et al. (2016). As shown in Table 9, feeding corn DDGS at maximum diet inclusion rates increase non-renewable resource use by 71 percent, non-renewable energy use by 68 percent, and global warming potential by 30 percent compared with the control corn-soybean meal diets, on a per kg of feed basis. However, including corn DDGS in the diets reduced acidification potential by 20 percent and eutrophication potential by 22 percent compared with the corn-soybean meal control and all other co-product diets. When environmental impacts were expressed on a kg of carcass weight basis, the impacts were less dramatic but in the same direction as when expressed on a per kg of feed basis.

Table 9. Average environmental impact per kg of feed of Canadian grower-finisher diets when co-product ingredients are included at maximum inclusion rates compared with a corn-soybean meal control diets. (adapted from Mackenzie et al. 2016)

Environmental factor	Control	Meat meal[1]	Bakery meal[1]	Corn DDGS[3]	Wheat shorts[4]
Non-renewable resource use, g Sb eq.	1.90	1.81	1.82	3.25	1.57
Acidification potential, g SO_2 eq.	5.71	5.30	5.32	4.46	5.03
Eutrophication potential, g PO_4 ep.	1.22	1.14	1.16	0.98	1.08
Global warming potential, kg CO_2 eq.	0.40	0.38	0.38	0.52	0.33
Non-renewable energy use, MJ	4.49	4.27	4.27	7.32	3.70

[1] Grower, finisher, and late finisher diets contained 5.0, 7.5, and 7.5 percent meat meal, respectively

[2] Grower, finisher, and late finisher diets contained 7.5, 10.0, and 10.0 percent bakery meal, respectively

[3] Grower, finisher, and late finisher diets contained 30.0, 30.0, and 20.0 percent corn DDGS, respectively

[4] Grower, finisher, and late finisher diets contained 30.0, 40.0, and 20.0 percent wheat shorts, respectively

Conclusions

The use of DDGS in diets for all food producing animals can contribute to improved environmental sustainability when using net energy and digestible nutrients when formulating precision animal feeds, which is essential to minimize excess excretion of nitrogen and phosphorus in animal manure. Although DDGS is relatively high in protein and low in lysine and other amino acids relative to the animal's requirements (swine, poultry and aquaculture), the widespread availability and cost effectiveness of synthetic amino acids allow nutritionists to reduce diet crude protein levels, meet all of the essential amino acid requirements and reduce nitrogen excretion in manure. For grazing ruminants, studies have shown that feeding DDGS not only improves growth and lactation performance, but also the urine and feces excreted from these animals can serve as an efficient and cost-effective way of providing nitrogen to growing pasture grasses and improve yields. One of the unique advantages of corn DDGS compared with other grains and grain-based ingredients is its relatively high total and digestible phosphorus content. Formulating swine and poultry diets on a digestible phosphorus basis and using phytase can significantly reduce manure phosphorus excretion. Furthermore, several studies have shown that feeding DDGS diets reduce methane emissions in ruminants, and ammonia and hydrogen sulfide emissions from swine and poultry manure. Initial studies comparing DDGS with other co-product or by-product ingredients indicate some additional advantages to minimize environmental impact of animal diets.

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CHAPTER 28

Factors that Affect DDGS Pricing and Transportation Logistics

Introduction

ONE OF THE BIGGEST FACTORS for determining whether DDGS is an economical animal feed ingredient in the international market are the price and transportation logistics to import DDGS. This chapter describes the current factors, challenges and pricing mechanisms for determining the destination cost of importing U.S. DDGS. Historically, the primary users of DDGS were the dairy and beef industries in the U.S. (Figure 1). However, beginning in 2003-2004, with new research information available on the benefits of using DDGS in swine and poultry diets, usage of DDGS in the swine industry began to increase dramatically, and to a lesser extent in the poultry industry. Today, the U.S. swine and poultry industries consume about 25 percent of the domestic DDGS market and this growing trend is likely to continue, especially when prices of competing ingredients, such as corn and soybean meal, are high and fluctuations in supply occur from year to year.

The U.S. production of ethanol and DDGS increased dramatically from 2001 to 2010, but since 2010 production has been relatively steady. As shown in Figure 2, growth of the U.S. ethanol industry has resulted in increases in DDGS production, as well as changes in the percentage of DDGS being exported. As the U.S. livestock and poultry markets achieve maximal market penetration for DDGS use, an increasing proportion of DDGS production will be exported. However, the amount of increase in DDGS exports will be highly dependent on the price relationship of competing ingredients in the international market as well as transportation costs.

Composition of Domestic Usage (One Thousand Short Tons DDGS Equivalent)

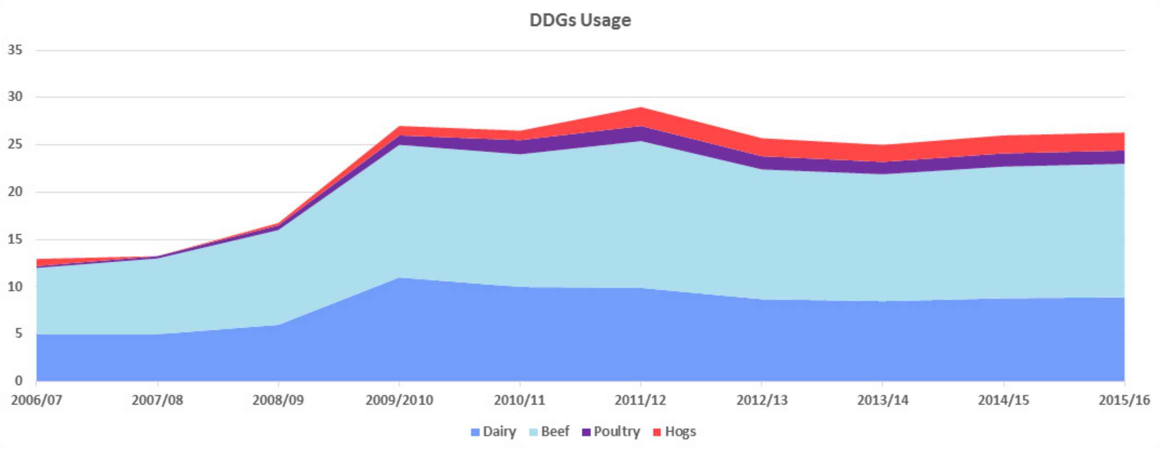


Figure 1. Historical consumption of DDGS with soluble in the livestock and poultry industries from 2006 to 2016 for the October to September crop Year (Source: Steve Markham, CHS Inc.)

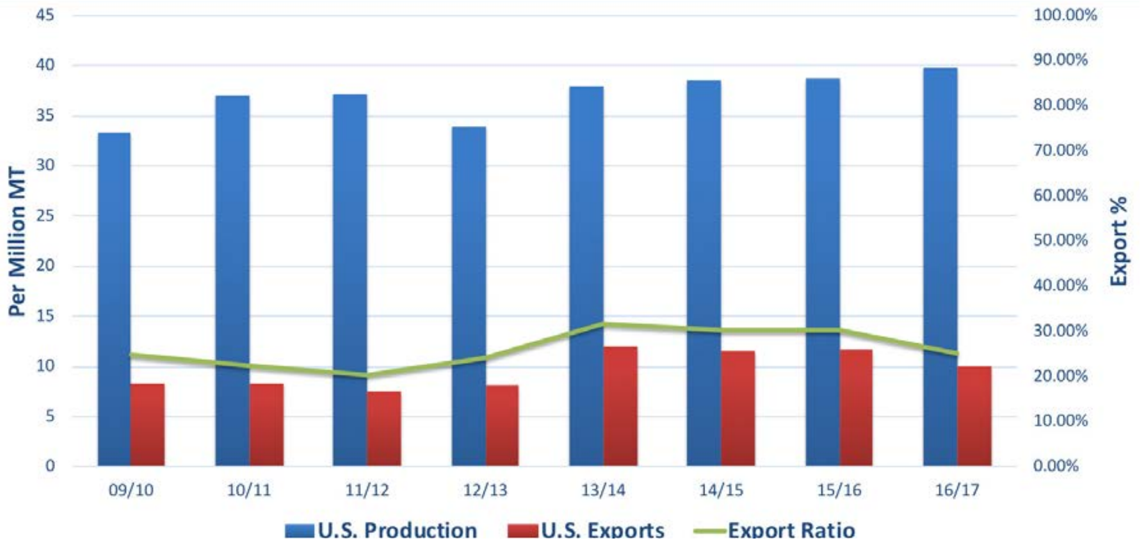


Figure 2. Estimates of historical and future trends in U.S. DDGS production and exports from 2009 to 2017 (Source: Sean Broderick, CHS Inc.)

Factors Affecting DDGS Price

A number of factors can affect DDGS pricing. First, it should be noted that the highest demand for DDGS is in the U.S., where about 75 percent of the distiller's grains produced today are consumed by livestock and poultry. As a result, about 25 percent of DDGS was exported in 2017. However, the amount of DDGS exported to other countries is increasing every year. Ethanol and co-product producers and marketers of DDGS are aware that the export markets are a very important component in overall DDGS demand.

DDGS is a very unique mid-protein, high-energy feed ingredient. It partially replaces corn, soybean meal and phosphorus supplements in animal feeds. Therefore, the price of DDGS is affected by several factors including: the market price of corn and soybean meal, availability of supply for export, seasonality of domestic DDGS consumption, fluctuating transportation costs and import tariffs imposed by many countries. Although many feed ingredient traders consider DDGS to be a "protein meal," and consequently compare it to soybean meal, it actually is more similar in nutritional and economic value to corn. In fact, the DDGS price follows the corn market more closely than the soybean meal market. Figure 3 shows historical corn and DDGS prices FOB at the Gulf of Mexico. Overall trends in both the corn and soybean meal markets affect the DDGS price, but daily volatility in the corn or soybean meal market on the Chicago Board of Trade does not always translate into daily volatility in price in the DDGS market. If corn and/or soybean meal prices are generally high relative to DDGS price, DDGS will often replace a larger proportion of corn and soybean meal in animal feeds (i.e. higher dietary DDGS inclusion rates).

The price of DDGS is also influenced by season of the year. Most of the domestic DDGS use is in cattle feeds. When cattle are moved to pastures for grazing during the summer months (May through October; Figure 4), the number of cattle on feed decreases causing the domestic demand for distiller's grains to decrease dramatically. This results in an increased supply available for the export market and usually results in lower DDGS prices compared to other months of the year. Lower elevation costs coupled with traditionally

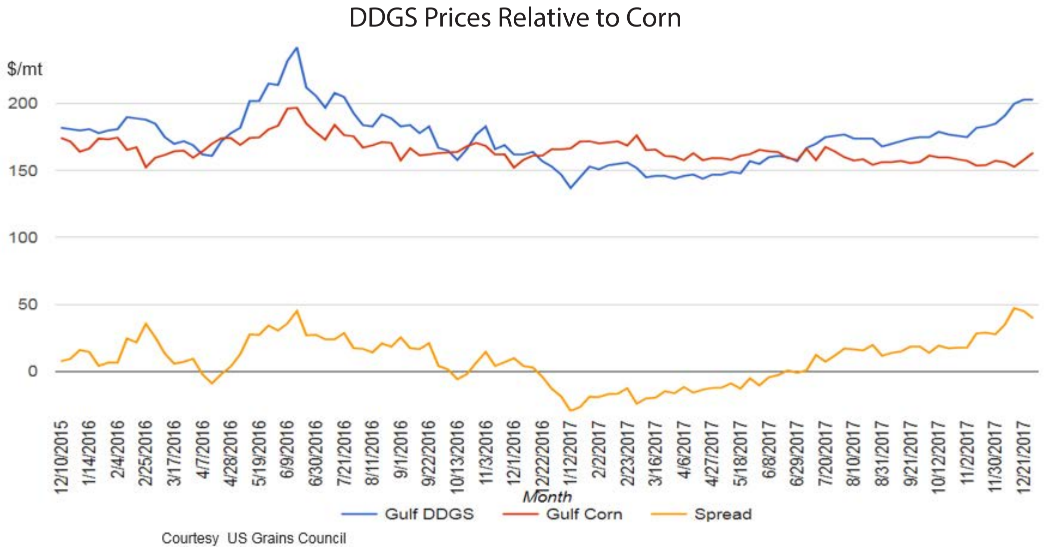


Figure 3. DDGS prices relative to corn in the US Gulf December 2015-January 2018 (Source: Steve Markham, CHS Inc.)

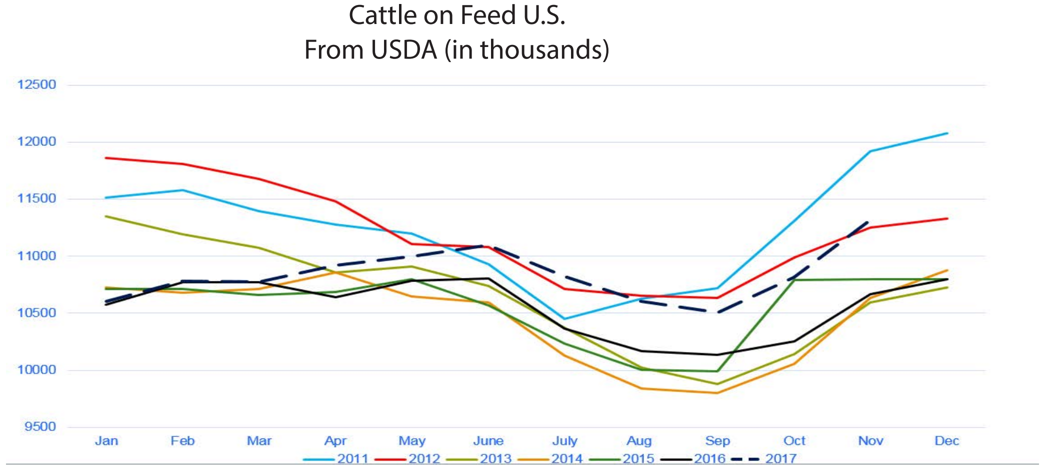


Figure 4. Seasonality of U.S. cattle on pasture vs. feedlots consuming high grain diets (Source: Sam Erwin, CHS Inc.)

lower barge freight during the summer months also adds to a more competitive DDGS value during this time period.

During seasonal price increases in the DDGS market, corn and soybean meal will be more price competitive with DDGS, resulting in less DDGS being used in least cost diet formulations. Strong demand in the early months of the year, coupled with historically short supplies at the same time, has typically caused higher DDGS prices in January through May. However, even though this has been a historical trend, it is not a certainty that DDGS will always be priced higher during this time of year. With the large quantities of DDGS being produced by the U.S. ethanol industry and supplied to the market, both buyers and sellers should not expect supply shortages normally seen in the late winter and spring. However, as the U.S. swine and poultry industries continue to use a greater share of total DDGS production, and since they are not associated with the grazing season like cattle, the seasonal effects on DDGS price will likely become less dramatic in the future. The DDGS export market also plays a big role in reducing the volatility of high and low prices in the U.S. market, and often results in exporting greater amounts of DDGS to other countries when domestic prices get too low.

Transporting DDGS

Barges and ocean vessels

Ocean freight rates, based on the Baltic Exchange Panamax Index, have varied dramatically over the past 10 years (Figure 5). For example, ocean charter vessels cost more than $94,000 per day in September 2007 and then dropped as low at $3,350 per day in December 2008, a little more than one year later. The high volatility in charter vessel freight has a major impact on the cost of obtaining DDGS for international customers. Current freight rates have increased substantially from the low point in January 2016, but are much more reasonable than the highest freight cost that occurred during the winter of 2010.

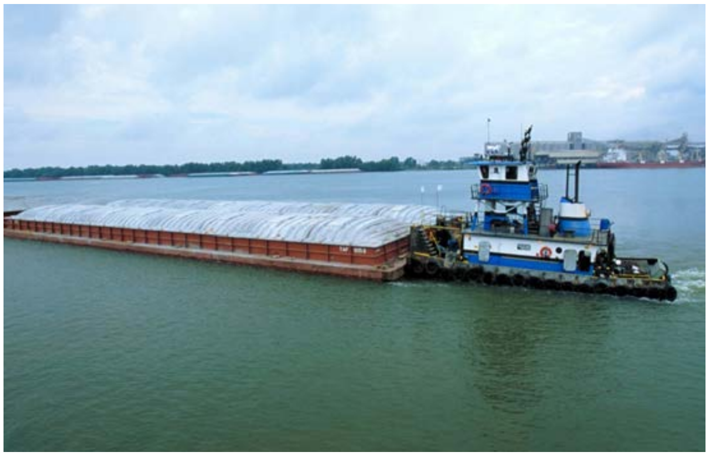


Photo Courtesy of Steve Markham, CHS Inc.

Figure 5. Baltic Shipping Index since 2009

One of the most cost-effective freight options available in the U.S. is to transport DDGS on the river system via barges, and then load it onto ocean vessels. Barge freight trades as a percentage of tariff, but these percentage rates fluctuate over time. Long trips (e.g. Minneapolis, Minnesota to New Orleans, Louisiana) will have a higher tariff and probably a higher percentage rate compared to transporting shorter distances from origins in more southern locations. The U.S. has 5,000 miles of navigable waterways for barges and tug boats, and different tariffs and percentage rates are traded for each navigable river in the U.S.

Barges traded to New Orleans are usually offered as CIF (Cost, Insurance, and Freight) to New Orleans (NOLA). A CIF price excludes loading the product onto the boat. In general, DDGS is loaded onto barges in the interior U.S. and shipped to the Port of New Orleans and surrounding areas where it is transferred into holds on ocean going vessels. This transfer is usually done using mid-stream loaders. Both barges and vessels are pulled up alongside the midstream loader where the transfer is made. Vessel sizes vary, but the most common vessel types are Handysize, Handymax and Panamax vessels. The Handysize vessel will hold 20,000 to 30,000 metric tons of cargo, whereas the Handymax holds 35,000 to 49,000 metric tons, and the Panamax holds 50,000 to 75,000 metric tons of cargo. One Panamax vessel will hold the DDGS equivalent of about the same amount contained in 37 barges or 555 rail cars. Ocean freight trades like a commodity and the rates change on a daily basis.

Ocean freight rates depend on a number of factors including, but not limited to:

- market conditions
- type of vessel needed
- port drafts
- port charges
- load terms
- discharge terms
- time of year

Factors affecting the overall ocean freight market include:

- supply and demand issues
- cost of vessel construction and operation
- new vessel construction vs. vessel retirements
- seasonal demand (e.g. grain harvest in North and South America)
- China's demand for all raw materials
- length of voyage
- turnaround time
- market psychology or expectations

Freight chartering options include:

- Voyage Charters – point A to point B shipments
  - less risky for cost calculations

- Time Charters – give more flexibility because the vessel is chartered for a specified amount of time rather than by the voyage
  - This option gives potentially higher risk and potentially higher reward. Once the cargo arrives to destination port it is unloaded via clam buckets which scoop the product out of the vessel, or it is unloaded pneumatically.

Containers

The United States is currently the world's largest container importer, which puts it in a very unique situation. Containers filled with electronics, textiles, auto parts, etc., arrive in the U.S. primarily from Asia, and they need to be shipped back to that region in order to be re-loaded with the same types of consumer goods for another shipment to the U.S. Steamship lines prefer to generate some revenue on the backhaul, rather than sending empty containers back to Asia which do not generate any revenue for them. This backhaul is where DDGS, along with other agricultural products, have found their niche in this freight market. The largest surpluses of empty containers in the interior U.S. are found in Chicago, Illinois and Kansas City, Missouri, followed by Memphis, Tennessee. The typical container export process is as follows:

1. DDGS is shipped from the ethanol plant to a facility dedicated to container loading. These facilities are typically located close to large container collection yards where the empty containers are stored.

2. In some cases, ethanol plants load containers with DDGS on site, thereby circumventing the costs associated with a third-party container loader.

3. Once containers are loaded with DDGS, they are shipped by trucks to the container collection yard and placed onto a rail chassis.

4. From there, containers are shipped by rail to a U.S. port to later be loaded onto a container vessel. Long Beach, California handles more containers than any other U.S. port. Typical transit time from Chicago to Long Beach is seven to 10 days. Typical transit time from Long Beach to Asian ports is 16 to 18 days.

Shipping via containers is an excellent option for the discriminating buyer who desires purchasing DDGS from a limited number of sources or ethanol plants.

Photo Courtesy of Steve Markham, CHS Inc.

Rail

Hopper rail cars are used to export DDGS to Mexico and Canada. Rail shipments of DDGS to Mexico are growing exponentially every year, and the number of rail car shipments to Canada is also increasing. Rail exports are considered to be the easiest transportation mode to manage considering the limited number of steps involved and the time in transit. Rail cars are loaded at the ethanol plant, billed with the railroad, and shipped to the final destination. Rail cars must be inspected and cleaned once they arrive at the border. Once inspected and cleaned, they cross the border and make their way to the final destination. The principal railroads serving the U.S. are Union Pacific (UP) and BurlingtonNorthern Santa Fe (BNSF). Mexico's main rail lines are Ferromex (FXE) and Kansas City Southern de Mexico (KCSM), formerly TFM. Canada's principal rail lines are the Canadian National Railway (CN) and Canadian Pacific Railway (CPR).

Challenges of Exporting DDGS: Perspectives from DDGS Exporters

Loading cost and efficiency

It requires twice as much time to load an ocean vessel with DDGS as it does with corn. Because elevation margins are expensive, this is one of the major cost contributors to DDGS transportation costs. For exporters that do not have control of elevators, events when vessels do not arrive on schedule can cause them to default on the loading. To avoid this situation, DDGS exporters must have the right vessel at the right time from the right owner with the barges, rail cars or boats waiting to load it. Timing is critical to minimize cost.

Photo Courtesy of Steve Markham, CHS Inc.

Containers

Very few containers return empty today as they did a few years ago. As a result, availability has been a challenge in the world economy, and has led to a real problem with on-time delivery. As a general rule, use of bulk vessels is less expensive, more dependable and usually easier to control DDGS quality, especially when a sample is obtained and tested before loading.

Many of the containers today are loaded directly at the ethanol plant. Even plants that do an excellent job at producing high quality DDGS can, occasionally, produce a less than desirable DDGS co-product on a given day, and that co-product can be loaded in a container without the marketer knowing it.

Containers being delivered to the right ship for a timely delivery can also occasionally be a problem as well as the possibility of freight rates changing at any time even after a container is loaded. Seasonality and variability in the container market occasionally causes disruption in the supply chain, including cancelled bookings and restricted availability in key origin markets.

Suggestions for Success in Importing DDGS

It is essential that DDGS importers know, and have a relationship with their supplier. Specifically, importers should understand the exporting company's logistical and transportation capabilities. If a DDGS exporter does not own export elevators, access to these elevators can be a problem. Currently, U.S. DDGS exporters have limited freight and elevation capacity because fewer elevators are available and record supplies of grain and grain co-products are being produced.

Exporters that have facilities and capabilities via multiple transit ways (Great Lakes, major rivers, Gulf of Mexico, Pacific Northwest) have a better ability to serve the export market around the globe. Purchasing DDGS at the lowest freight costs will require working with companies that have multiple transportation and loading options and flexibility.

Suppliers who market for specific ethanol plants have control over the origin of DDGS sources and can more easily control the quality of DDGS that is delivered. Buyers who purchase through brokers or other suppliers that do not have direct marketing agreements with ethanol plants cannot easily control the quality of DDGS being delivered. It is also possible for DDGS marketers that control the supply sources to send DDGS samples at the time of origination, to reputable commercial laboratories for testing and send results directly to the customer before a vessel or hold is loaded. It is important to identify and agree on a reputable third party commercial laboratory for sample analysis to avoid potential problems upon arrival at the destination.

Mycotoxin testing can be conducted on samples obtained at origin, or the supplier can provide the procedures and limits for corn used at the ethanol plants where the DDGS was produced. Color scores can also be determined for the DDGS customer using Hunter or Minolta color score measurements. Protein and fat guarantees should always be agreed upon before consummating a trade.

DDGS Unloading

Photos Courtesy of Steve Markham, CHS Inc.

CHAPTER 29

Summary of U.S. Grains Council Sponsored International Reduced-Oil DDGS Feeding Trials

Introduction

SEVERAL U.S. GRAINS COUNCIL (USGC) FEEDING TRIALS have been conducted to evaluate DDGS in Japan, Mexico, and Vietnam since 2010. This chapter provides a brief summary of the key findings of the trials. Additional information on USGC sponsored feeding trials from previous years are summarized in the third edition of the USGC DDGS Handbook published in 2012.

Recent Demonstration Trials in Japan

Swine

Effect of low-fat DDGS fed during the first half of fattening period on growth performance and carcass characteristics

ABSTRACT

An experiment was conducted at Nihon University, College of Bioresource Sciences in Japan to evaluate the effect of feeding swine low-fat DDGS on growth performance during the first half of the fattening period. The control group was not fed any DDGS in both the first half and the second half of the fattening period. The experimental group was fed 20 percent DDGS diet during the first half of the fattening period and both groups were fed the same diet during the second half of fattening period. The genetic background of the pigs used in this experiment were Landrace (L), Large White (W) and crossbred (LW) pigs (n = 67), and were divided into the control group and experimental group and fed their respective diets. The initial body weight was 50 kg, and the time period up to when they reached 75 kg in body weight was called the first half of the fattening period, and the period of time before reaching 115 kg in body weight was the second-half period, during which respective experimental diets were fed. Body weight, number of days fed experimental diets, carcass weight, backfat thickness, and grade were recorded for each pig. Nine Landrace barrows from each group were used for carcass analysis. The weight gain was favorable in both groups with average daily gain of 0.9 kg/day during the first half of the feeding period, and which was slightly decreased during the second half of the feeding period. There were no differences in feeding days, daily weight gain and feed conversion ratio between the two groups during the first half, second half or the entire feeding period. Also, there were no differences observed in carcass characteristics, analytical values of the carcass parts suitable for roasting including heat loss rate, texture, color tone (L*, a*, b*), fat melting point and fatty acid composition. The results indicate that feeding the 20 percent DDGS diet during the first half of the fattening period did not cause any negative effect on growth performance and provided the same level of productivity and carcass composition that would have been obtained with feeding standard diets in the Japanese pork industry.

MATERIALS AND METHODS

The objective of this study was to determine the effect of feeding a low-fat DDGS diet in the first half of the fattening period on swine growth performance and carcass characteristics. This feeding trial was implemented at the feedlot of Kanagawa Prefectural Pork Producers Association (Ebina City, Kanagawa Prefecture) from September 2015 to January 2016 (Photo 1).

Grouping and control of experimental pigs
A total of 67 pigs consisting of Landrace (L), Large White (W) and crossbred (LW) swine were divided into two groups: first group (25 head) starting the experiment on September 2015 and second group (42 head) starting on October 2015. The pigs within each group were allotted to either of the control group or experimental group, ensuring equal distribution in terms of breed, sex (sow/barrow) and body weight as much as possible, and then three pigs were housed in each cell. Ear tags were used for identification purpose. Starting with the initial body weight of 50kg, the period up to the time when the pigs would reach 75 kg was set as the first half of the fattening period and the period up to the time when they would reach 115 kg was as the second-half fattening period. During those periods, the pigs were fed respective diets. The first diet was replaced with the second diet when the average weight of the pigs in each cell reached 75 kg which was set as the first goal. Thereafter, when the weight of each pig reached115 kg, it was moved to a private cell and then shipped to a meat center. The pig was slaughtered on the day or next day of the shipment, and its carcass grade was recorded.

Experimental diets

The composition of experimental diets (Photo 2) is shown in Table 1. The control group was not fed any DDGS in both the first half and the second half of the fattening period. The experimental group was fed 20 percent DDGS diet during the first half of the fattening period and both groups were fed the same diet during the second half of fattening period. The diet of the experimental group for the first half of the fattening period was formulated so that TDN and protein were included at the same level as those of diets for the control group on the assumption that soybean meal, the main ingredient of the diets for the control group, was replaced.

Growth performance measurements

Body weight was measured every week and pigs with a weight close to the target weight for shipment (115 kg) were measured as appropriate. The feeding amount was measured for each group, and other measuring items such as age in days and daily weight gain were measured individually. Since all pigs in a cell were not always simultaneously shipped, the individual feeding amount for each was obtained by dividing the total feeding amount by the number of pigs remained in the cell as of the measuring day.

Carcass measurements

Carcass weight, backfat thickness and grade at the time of slaughter were recorded for all pigs. The carcass was analyzed using nine Landrace barrows each from the control group and experimental group. The part suitable for roasting in the left carcass of each was divided into three parts (shoulder, back and loin) and the back part was used for the analysis. The analytical items included heat loss rate, texture and color tone (L, a, b) of the eye muscle (ribeye) of the part for roasting (back), and color tone (L. a, b), fat melting point and fatty acid composition of the inner layer of back fat. The heat loss rate was calculated using the formula: weight of the lump of pork meat before heated – weight of the lump of pork meat after heated) / weight of the lump of pork meat before heated x 100. Texture was measured using a Tensipresser. Color tone was tested using a color-difference meter. Melting point of fat was measured by the method specified in the Standard Methods of Analysis for Hygienic Chemists (version of 1990). Fatty acid composition was analyzed by a gas chromatography.

Statistical analysis

The difference of average values between the control group and experimental group was confirmed by t-test.

RESULTS AND DISCUSSION

The general ingredients of the diets formulated for the experiment are as listed in Table 2. The experimental results of the pigs are summarized by breeding group and sex in Table 3. Barrows show fewer days required up to slaughter, greater daily weight gain and thicker backfat than sows. The results are similar to those commonly seen in the fattening performance of general swine on feed, and no difference in average values is observed between the breading groups. Therefore, the results described hereafter are obtained from the average values of all the pigs under experiment.

Growth performance

Weight gain is shown in Table 4. The experiment started with the body weight of 50 kg and the diet was changed to the one for the second half of the fattening period when the body weight exceeded 75 kg. After confirming that the weight reached 115 kg, pigs were shipped. The times for starting the experiment and changing diets were controlled using the average values of respective groups while shipment of pigs was individually controlled. This explains the smaller standard deviation of body weight at shipment. The fattening period is 82 days in total for each group, which shows no difference between the groups. Daily weight gain is 0.84 kg for the control group and 0.83 kg for the experimental group, which are similar. The final ages at slaughter also does not show any significant difference. The comparison between the first and second halves of fattening period shows favorable body weight gain in both of the experimental group and control group during the first half of the period, which are 0.93 kg and 0.96 kg, respectively, and a slight decrease in the second half period, 0.79kg and 0.76 kg respectively. Feed conversion ratios of both groups also show relatively low and good values of 3.37 and 3.11 during the first half of the period and aggravates up to 3.9. during the second period.

Carcass characteristics

No significant differences in carcass weight, dressing percentage or backfat thickness were observed between the two groups, which means the carcass characteristics show common values. As to the carcass grading, the percentage of upper grade carcass of each group is not high, but the percentage of middle grade carcass of the experimental group is higher than that of the control group, resulting in a higher percentage of lower-grade meat of the control group. The reason for carcass being excluded from the grading system was fat covering. The lower percentage of upper grade carcass as a whole is explained by the larger number of pureblood pigs than crossbred pigs used for the experiment due to reasons of the experimental farm. Although the reason for the higher percentage of middle grade carcass of the experimental group than the control group is unknown, the favorable average feed conversion ratio of the experimental group during the first half of the fattening period may contribute to achieving the suitable body form for the grading standards.

Nine Landrace barrows from each group were used for the analysis of meat quality of the part suitable for roasting, and the results of analyzing the eye muscle (ribeye) are shown in Table 4. There were no substantial differences in any items (Photo 3). Table 5 shows the results of analyzing the inner layer of backfat of the part suitable for roasting. There are also no substantial differences in the analyzed items. The fat melting point is about 37℃ that is desirable and far from lower values of around 30℃ in which case the quality of fat is close to the level of so called loose fat. The results of the analysis of fatty acid composition (Table 6) also indicate a standard level of fatty acid composition that contains less polyunsaturated fatty acids (linoleic acid, linolenic acid, etc.), more monounsaturated fatty acid (oleic acid) and more saturated fatty acids (palmitic acid and stearic acid).

CONCLUSION

This study indicates that an inclusion of 20 percent low-fat DDGS in the diets fed to swine during the first half of the fattening period does not give any negative effect on fattening performance and keeps the productivity level equal to that of commonly used diets.

Table 1. Composition of Diets Formulated for Experiment (percent, as is basis)

	Diet for 1st half period		Diet for 2nd half period
	Control diet	Experimental diet	
Low-fat DDGS	-	20.00	-
Corn	56.28	47.73	56.22
Milo	20.00	20.00	20.00
Soybean meal	16.00	4.35	14.40
Bran	3.00	3.00	7.00
Fish meal (CP 65 percent)	2.00	2.00	-
Calcium carbonate	0.88	1.10	0.98
Dicalcium phosphate	0.41	0.15	0.48
Animal fat	0.50	0.50	-
Salt	0.30	0.30	0.30
L- Lysine hydrochloride	0.03	0.27	0.02
B-complex vitamins	0.20	0.20	0.20
Vitamin ADE	0.20	0.20	0.20
Microminerals	0.20	0.20	0.20
	100.00	100.00	100.00

Nutrient adequacy
(Values calculated based on the Feed Composition Table and Japanese Feeding Standard)

Total digestible nutrients (TDN)	104.0
Crude protein (CP)	103.0
Calcium	107.7
Lysine	108.8

Table 2. General Ingredients of Diets Formulated for Experiment (percent, as is basis)

		Diet for 1st half period		Diet for 2nd half period
	DDGS	Control diet	Experimental diet	
Moisture	15.3	13.3	13.3	13.3
Crude protein	26.9	14.9	14.2	13.2
Crude fat	9.7	4.3	5.7	4.2
Crude fiber	5.3	1.8	2.1	2.0
Soluble nitrogen-free extract	38.4	61.9	60.9	63.6
Ash	4.4	3.8	3.8	3.7

Table 3. Comparison of Results by Breeding Group and Sex

	Sex	Number of animals	Ages at slaughter (day)	Daily weight gain (kg)	Backfat thickness (cm)
Control group					
Landrace (L)	Gilt	8	203	0.76	2.0
	Barrow	9	185	0.89	2.6
Large White (W)	Gilt	8	189	0.86	2.3
	Barrow	5	187	0.86	2.3
Crossbred (LW)	Gilt	1	185	1.04	2.3
	Barrow	2	193	0.88	3.1
Experimental group					
Landrace (L)	Gilt	8	200	0.80	2.2
	Barrow	9	188	0.87	2.6
Large White (W)	Gilt	7	192	0.82	1.9
	Barrow	4	190	0.88	2.3
Crossbred (LW)	Gilt	5	194	0.85	2.4
	Barrow	1	185	0.93	3.0

Table 4. Weight Gain and Carcass Characteristics

	Control group (n=33)	Experimental group (n=34)
Body weight at start (kg)	50.1 ± 5.8	49.6 ± 6.6
Body weight at diet change (kg)	78.2 ± 6.1	79.2 ± 7.0
Body weight at shipment (kg)	117.2 ± 3.0	116.9 ± 2.7
Fattening period (days)	82 ± 14	82 ± 12
1st half	31 ± 5	32 ± 6
2nd half	51 ± 12	50 ± 11
Feeding amount (kg)	245.2 ± 47.5	235.8 ± 34.1
1st half	92.1 ± 20.3	89.9 ± 15.0
2nd half	153.1 ± 43.8	145.9 ± 32.3
Daily weight gain (kg)	0.84 ± 0.11	0.83 ± 0.09
1st half	0.93 ± 0.27	0.96 ± 0.21
2nd half	0.79 ± 0.14	0.76 ± 0.13
Feed conversion ratio	3.61 ± 0.60	3.49 ± 0.38
1st half	3.37 ± 0.93	3.11 ± 0.69
2nd half	3.94 ± 0.93	3.95 ± 0.90
Slaughter age (days)	192 ± 19	193 ± 16
Carcass weight (kg)	77.5 ± 3.0	77.8 ± 2.4
Dressing percentage (%)	66.1 ± 1.7	66.5 ± 1.4
Backfat thickness (cm)	2.4 ± 0.6	2.3 ± 0.5
Grade (number of heads)		
Upper	6	5
Middle	14	19
Lower	10	7
Out of grade	3	3

Average ± Standard deviation

There were no signficant differences between dietary treatments for all measurements

Table 5. Heat Loss, Texture and Color Tone of Eye Muscle (Ribeye)

	Control group	Experimental group
Heat loss (drip rate) %	7.2 ± 1.4	8.4 ± 1.2
Texture		
Hardness (kg/cm^2)	7.95 ± 0.76	8.37 ± 1.20
Cohesiveness	0.50 ± 0.03	0.51± 0.03
Elasticity %	81.2 ± 1.6	80.8 ± 1.6
Adhesiveness (cm^2/cm^2)	0.00 ± 0.01	0.00 ± 0.00
Color tone		
L	51.8 ± 2.7	51.9 ± 2.6
a	10.5 ± 1.1	10.4 ± 0.8
b	10.8 ± 1.2	10.6 ± 1.0

Average ± standard deviation n = 9

There were no signficant differences between dietary treatments for all measurements

Table 6. Color Tone, Melting Point and Fatty Acid Composition of Inner Layer of Subcutaneous Fat

	Control group	Experimental group
Color tone		
L	80.3 ± 1.5	79.5 ± 0.9
a	6.7 ± 1.4	6.8 ± 1.0
b	9.9 ± 1.9	10.4 ± 1.8
Fat melting point (℃)	37.7 ± 1.3	37.0 ± 1.9
Fatty acid composition %		
10:0 (Decanoic acid)	0.1 ± 0.0	0.1 ± 0.0
12:0 (Lauric acid)	0.1 ± 0.0	0.1 ± 0.0
14:0 (Myristic acid)	1.3 ± 0.1	1.4 ± 0.1
16:0 (Palmitic acid)	27.0 ± 0.7	26.9 ± 0.8
16:1 (Palmitoleic acid)	1.5 ± 0.2	1.6 ± 0.2
17:0 (Heptadecanoic acid)	0.3 ± 0.1	0.3 ± 0.1
18:0 (Stearic acid)	16.8 ± 1.0	15.9 ± 0.9
18: 1(n9) (Oleic acid)	39.4 ± 0.8	39.4 ± 1.2
18:2 (n6) (Linoleic acid)	7.7 ± 0.6	6.7 ± 0.7
18:3 (n3) (Alpha-linolenic acid)	0.4 ± 0.0	0.4 ± 0.1
20:0 (Arachidic acid)	0.3 ± 0.0	0.3 ± 0.0
20:1 (Icosenoic acid)	1.1 ± 0.1	1.0 ± 0.1
20:2 (n2) (Icosadienoic acid)	0.4 ± 0.1	0.4 ± 0.1
20:4 (n6) (Arachidonic acid)	0.1 ± 0.0	0.1 ± 0.0

Average ± standard deviation n = 9

There were no signficant differences between dietary treatments for all measurements

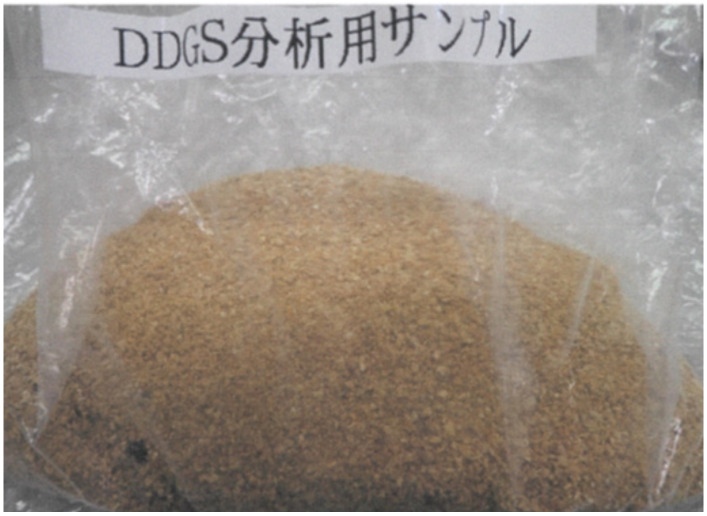
Photo 1. Site of Feeding Experiment

Pigpen

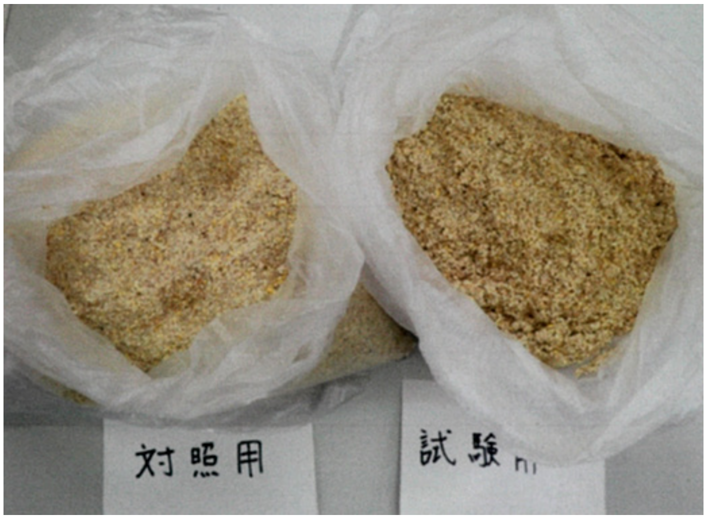
Cell

Measurement of body weight

Photo 2. DDGS Samples and Diets



DDGS (experiment sample)



Control diet and experimental diet for first half period

Feedstuff

Photo 3. Carcass

Cuts suitable for roasting

Recent Demonstration Trials in Mexico

Beef Cattle

TRIAL 1

A demonstration study was conducted in 2014 to evaluate supplementing diets with one kilogram of DDGS per day or a concentrate containing meat and bone meal and DDGS on growth performance and compensatory growth of the bulls under different weather conditions. It is well known and documented that meat and bone meal has a very low digestibility, and in several companies the use of ruminant meat and bone meal in ruminant diets is not allowed because of the concern of transmission of BSE. The results from this demonstration trial are shown in Figure 1. Although the bulls fed DDGS began the trial with almost 38 kg less body weight, by the end of the trial they weighed about 24 kg more the bulls on the control treatment.

There are several important aspects regarding the improvement in average daily gain observed when feeding supplemental DDGS to these bulls. First, these bulls were extremely underfed and had a very low plane of nutrition. Both the control and DDGS supplemented groups arrived with the same body conditions. Once the bulls were adapted to the new paddocks and fed the supplement, they exhibited an extraordinarily high average daily gain (test day 29) that may be explained as compensatory growth (Figure 2). Secondly, by the second test weigh date (day 55), the weather conditions were hot and dry, reducing the available forage resulting dramatically reduced average daily gain. However, in both feeding periods, the bulls fed supplemental DDGS gained 500 more grams/day in each period. As a result, providing the DDGS supplement increased net income by about $15/day (Table 1 and Figure 3). In addition to the economic benefits of using the DDGS supplement, at the end of the feeding trial, the control bulls weighed 24.5 kg less, and were gaining only 0.48 kg/day. Therefore, the control bulls required an additional 51 days to reach the same final weigh of the bulls fed the DDGS supplement. At times of the year when beef feedlots require large numbers of cattle; the price increases to meet this demand. Because of feeding the DDGS supplement, this producer had a great opportunity to sell heavier animals which were already adapted to start eating from a feed bunk. This advantage may result in five days less time at the feedlot for adapting to feeding, which is an economic benefit of about $15.24 pesos per animal per day.

Another feeding trial was conducted with beef producers near the Albagran feed mill in 2016. A group of DDGS users was formed, and cattle from different producers were transported to a single feedlot. Cattle weighing less than 230 kg receive the highest price and were used in this demonstration trial. A total number of 51 young crossbred bulls were housed in two feedlot pens (No. 6 and No.7). Once the bulls were received at the feedlot, they were checked by a veterinarian and admInistered several vaccines and vitamins, and sorted according to body weight into each pen, with light weight bulls (136 kg) being placed in pen No. 6 and the heavy bulls (168 kg) placed in pen No.7. During the first day, all bulls were fed 70 percent of formulated diet as an adaptation period. All animals in each pen had free to access to water and to the total mixed ration (TMR). The concentrate and TMR formulation is shown in Table 2. The bulls were fed at two to three times daily and individually weighed during the 53 day trial. Bulls consumed an average of 7 kg of TMR/ day and overall average daily gain was 1.17 kg/day. Final body weights were 194 kg for light weight bulls and 234 kg for heavy weight bulls. The economic evaluation showed that feeding

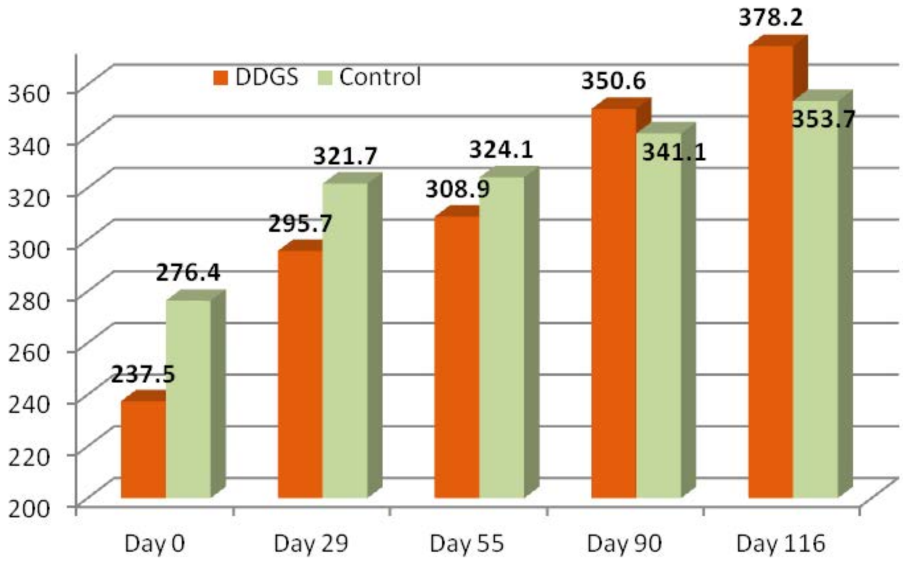


Figure 1. Initial body weight (kg) and subsequent body weights of bulls fed supplemental DDGS from February 28 to June 24, 2014

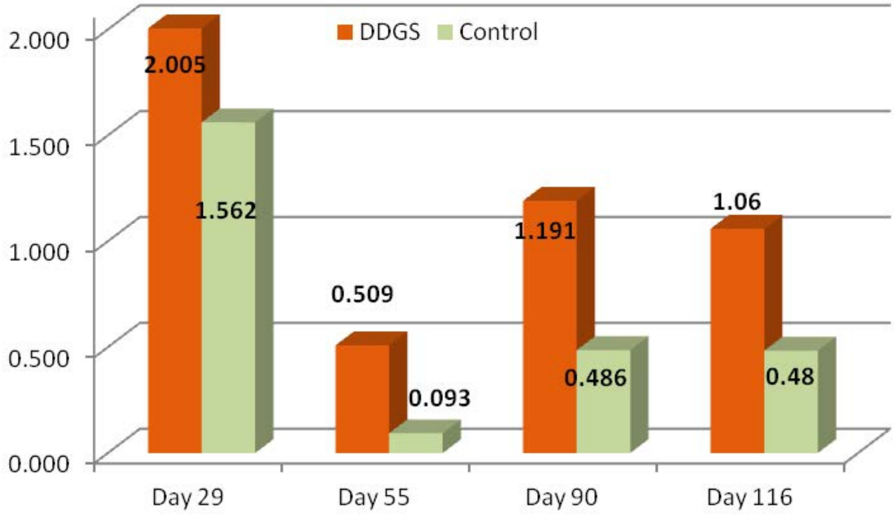


Figure 2. Average daily gain of bulls fed supplemental DDGS compared to the control group from February 28 to June 24, 2014

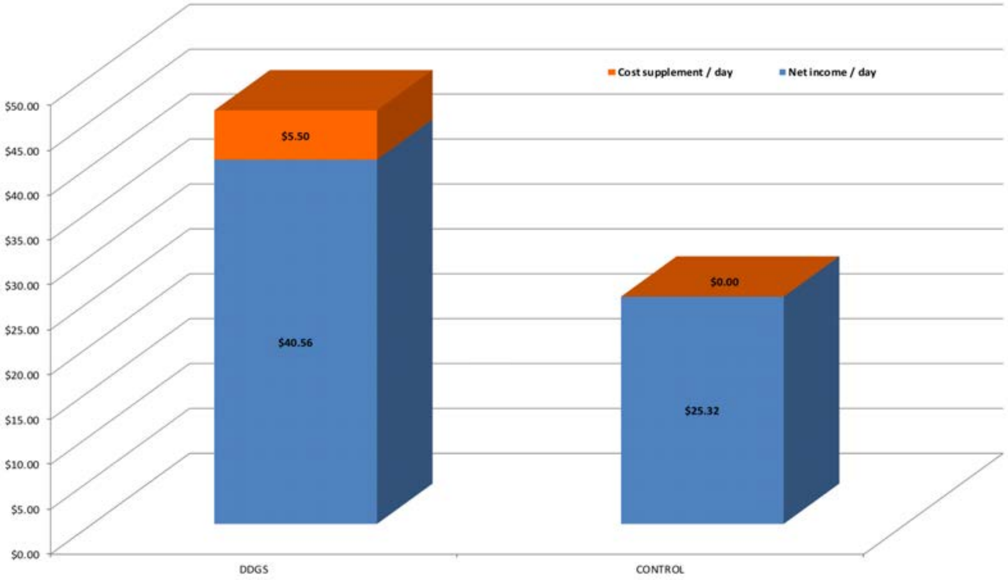


Figure 3. Average net income (Mexican pesos) per day per animal

Table 1. Summary of growth performance and economics of feeding supplemental DDGS to bulls

	DDGS	Control
Initial weight (kg)	237.5	276.4
Final weight (kg)	378.2	353.7
kg gained	140.6	77.3
Total days	116	116
ADG kg	1.212	0.666
$/kg live weight	$38.00	$38.00
Gross income/day	$46.06	$25.32
Cost supplement/day	$5.50	
Net income/day	$40.56	25.32

the DDGS concentrate resulted in a gross income of $61.03/day/bull Mx pesos, and subtracting the input costs of $40.49/day/bull Mx pesos, resulted in a net Income of $20.54 Mx pesos/day/animal (Table 3).

TRIAL 2

A demonstration study was also conducted in 2017 with replacement heifers in Tierra Colorada, Veracruz. In the state of Veracruz, most of the ranches are dedicated to the milk production as a cow calf operation or dual purpose farming, where the cow is milked three teats once daily, and the fourthteat is left for the nursing calf. These types of farms also raise the calves until they reach a wide range of live weight from 225 kg to 400 kg. The decision to sell the calves over this weight range is based on the economic needs of the farmer, and the price paid for these types of calves. However, every year the demand for replacement heifers remains. fairly constant and there is almost no management control of these animals. Although there are general guidelines to raise the replacement heifers, but most producers seem knowledgeable but others do not provide much attention to the heifers. Ideally replacement heifers must reach 60 percent of the mature body weight by the age of 15 months, and have a minimum hip height of 145 cm to be considered for first service. Most of the mature cows in Tierra Colorada average 555 kg. Therefore, 60 percent of this body weight is 330 kg, which is used as a general indicator that achieving a body weight of 350 kg at 15 months of age is the target to get heifers pregnant for the first time.

In December of 2016, the owner of this ranch agreed to conducting a DDGS feeding trial with a group of 100 replacement heifers. The initial age and body weight range of these heifers is shown in Table 4. A comparison of actual to ideal body weight of heifers at the Tierra Colorada ranch is shown in Figure 4.

The trial began with 100 virgin replacement heifers from a wide range of ages and weight, with the objective of comparing the current feeding practices with a proposed one involving feeding high levels of DDGS to increase average daily gain and reach the ideal body weight for first service on the right age. However, because infeasible to have different groups according to the age of the animals, heifers were sorted by body weight into two groups consisting of light body weight (50 heifers, 214 kg average initial body weight, and average age of 13.3 months) and the heavy body weight (50 heifers, 275 kg average initial body weight, and average age of 16.6 months).

Table 2. Concentrate and total mixed ration formulation

Ingredient	kg / MT
Concentrate Formula	
DDGS	350
Steam flake yellow corn	328
Wheat bran	110
Sugarcane molasses	100
Soybean meal	85
Mineral premix	27
Total	1,000
Total Mixed Ration TMR	
Chopped grass hay	165
Concentrate	835
Total	1,000

Table 3. Economic evaluation of DDGS feeding program for gowing bulls

Purchasing price/kg	$52.00
Selling price/kg	$52.00
Initial weight kg	150.6
Final weight kg	212.8
Supplement/animal/day kg	7.1
Average daily gain kg	1.174
Bank interest	$2.610
Cost supplement/animal/day	$32.802
Miscelaneus costs	$5.074
Total inputs	$40.486
Gross income	$61.026
Net income	$20.540
Feeding days	53.0
Total Money Invested/Period	
$/Bank interest period	$138
$/DDGS supplement period	$1,739
$/Miscellaneous period	$269
Sub total	$2,146
Purchasing money/bull	$7,831
Total amount money/period	$9,977
Gross income	$11,066
Difference	$1,089
Turn over money/year	6.887
Net income/year	$7,497
Cost/kg gained	$34.50

Table 4. Initial age and body weight of heifers at the beginning of the field demonstration trial in Tierra Colorada, Veracruz

Age range months	Number of heifers	Average body weight kg
8 to 10	12	206
11 to 12	22	238
13 to 14	11	228
15 to 16	25	256
17 to 18	24	282
19 to 20	5	300
21 to 22	1	240
Total	100	254

Heifers in both of these groups had been underfed with low average daily gain. For one month after beginning the trial, heifers were fed according to the traditional feeding practices, which consisted of only grazing grass pasture. After this initial month, all heifers were weighed, and the light heifers gained only 4.4 kg while the heavy heifers gained 10.6 kg during this one month period. With this low weight gain, it would require 951 days for the light weight heifers to reach 350 kg in body weight and 198 days for the heavy weight heifers. With this information, the farmer realized that the grass pastures were not providing enough forage to support a minimal 0.65 kg daily gain.

Although it is extremely difficult to calculate the actual dry matter intake from grass pastures, a forage and concentrate mixture was formulated for these heifers that included DDGS (Table 5). The amount of this mixture that was offered changed during the trial and was based on the average daily gain (ADG) of the heifers each month. The cost was $3.878

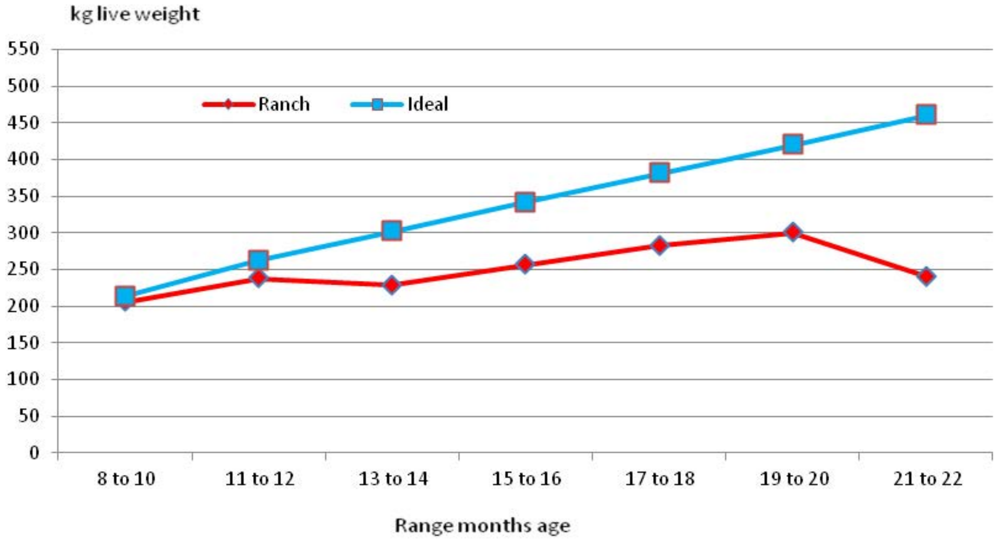


Figure 4. Comparison of actual to ideal body weight of heifers at the Tierra Colorada ranch

Table 5. Diet composition fed to replacement heifers

Mx $ / MT	Ingredient	kg / MT
650	Corn silage	100
4,035	Yellow corn	350
4,673	DDGS	405
2,725	Sugarcane molasses	125
10,156	Mineral premix	20
	Total	1,000

Mx pesos per kg and was offered at 3.5 kg per animal per day, which resulted in a cost of $13.573 Mx pesos per animal per day. The trial was conducted for 151 days until May 19, 2017.

The initial daily gain recorded on January 20, 2017 served as a reference for the demonstration. The light heifer group began with an average initial body weight of 219 kg and had an average final body weight of 313 kg. The heavy heifer group had an initial body weight of 285 kg and a final average body weight of 393 kg. Therefore, the light weight heifers gained 94 kg and the heavy weight heifers gains 108 kg during the 199 day feeding period, which resulted in an ADG of 0.79 kg/day and 0.90 kg/day for the light and heavy heifer groups, respectively. During the month of April, the entire heavy weight group reached the 350 kg and began their reproductive program. By January 20, 2017, this group was projected to reach the 350 kg in January 2018 (198 days), according to the previous daily gain; in contrast with 94 days needed to reach the 350 kg during the present demonstration, which represents a 104 days less to start the reproductive program. In comparison, the light weight heifer group still needed 153 days to reach the 350 kg, compared with the 951 days projected when the demonstration started. Figure 5 shows the average body weight increase during the demonstration trail for replacement heifers fed the DDGS diet at Ranch Tierra Colorada, and Figure 6 shows the reduction in the number of days to reach 350 kg body weight. By the end of the demonstration period, almost all of the heifers reached the desired body weight according to their age. Figure 7 shows the ideal age and body live weight (blue line), the red line shows the original increase in body weight of the light weight heifer group according to heifer age prior to the trial, and the green line shows the time point when heifers reached 350 kg for first service.

Table 6 and 7 show the economic comparison of providing the DDGS supplement to replacement heifers on this ranch. For both heifer groups, the net income was dramatically increased by feeding the DDGS supplement to these heifers, with the light weight heifers going from a loss to a net profit.

TRIAL 3

USGC DDGS field demonstration in Ozuluma Veracruz from February 23 to June 26, 2017

The Veracruz state is almost 850 km long (528 miles) surrounding the Gulf of Mexico. The west side of the state is located the Sierra Madre Oreintal and on the east side the Mexican Gulf shore. This particular geographic location allows the Veracruz state to receive large amounts of rainfall

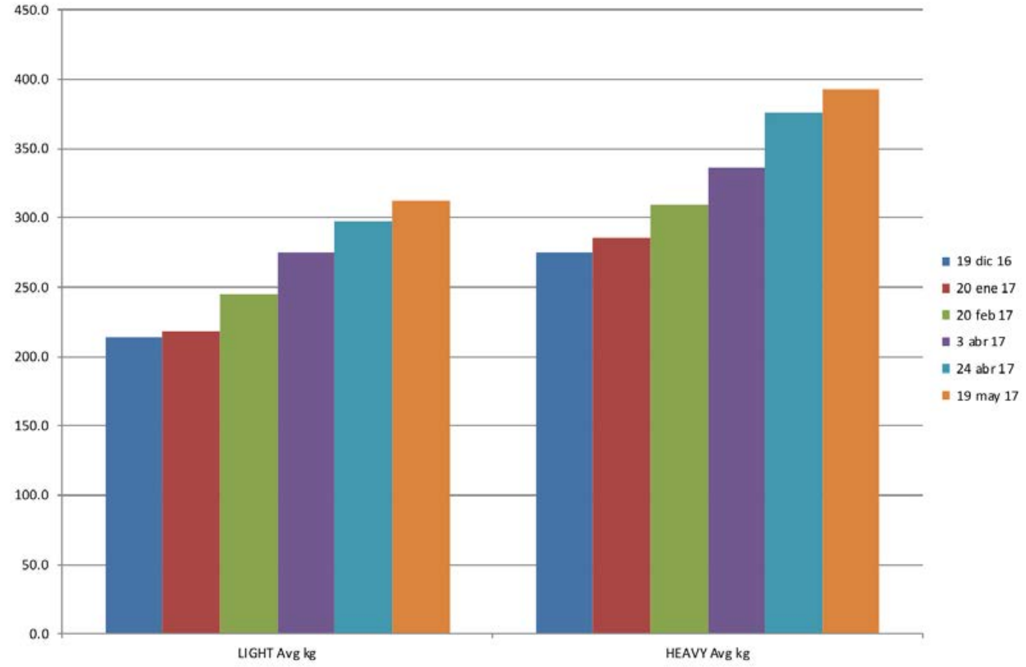


Figure 5. Comparison of the average body weight increase of light and heavy weight replacement heifers during the DDGS demonstration trial at Ranch Tierra Colorada

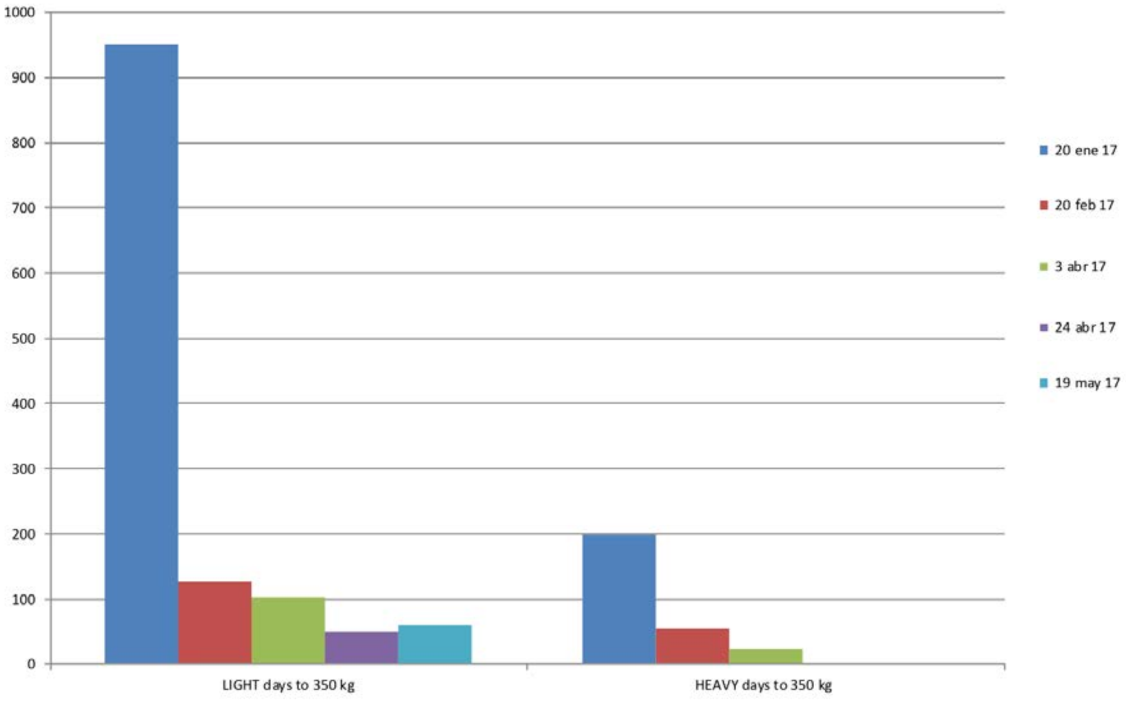


Figure 6. Comparison of the reduction in the number of days to reach 350 kg of light and heavy weight replacement heifers during the DDGS demonstration trial at Ranch Tierra Colorada

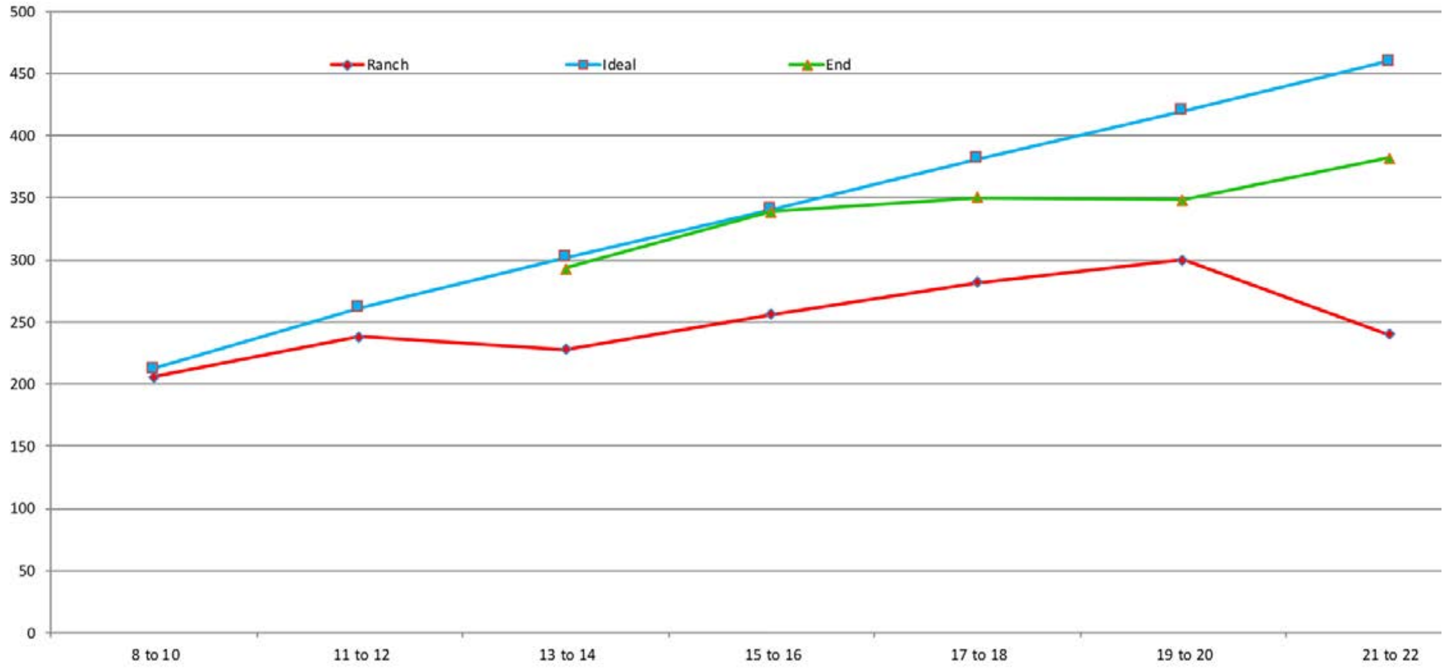
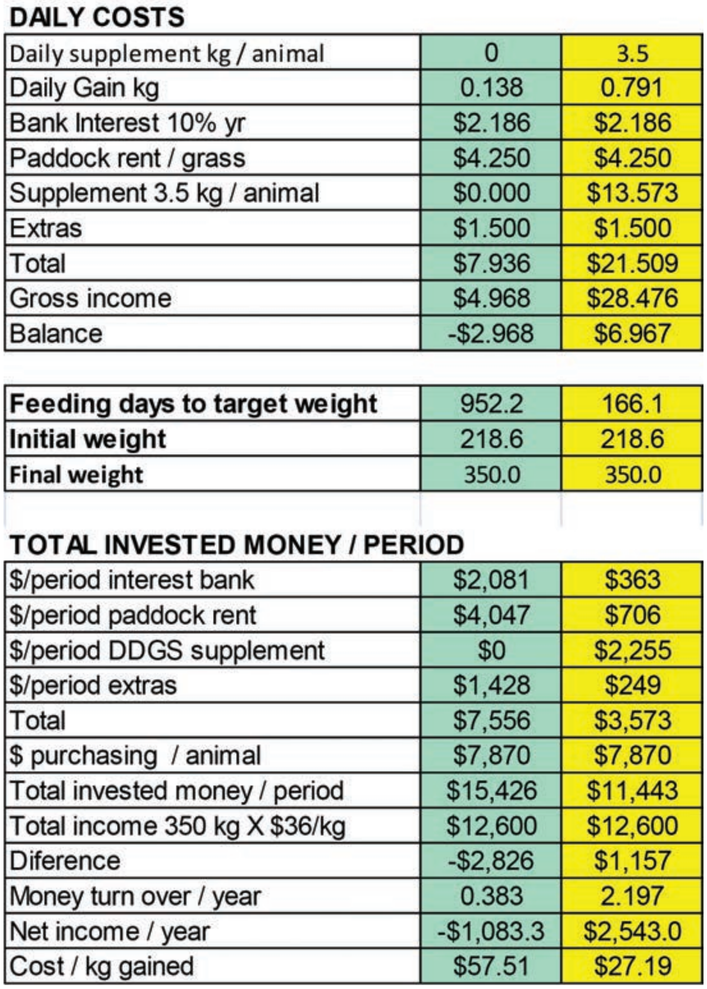


Figure 7. Comparison of the weight gain scenarios to reach ideal body weight (350 kg) of replacement heifers during the DDGS demonstration trial at Ranch Tierra Colorada

Table 6. Economic cost summary of the light weight heifer group



DAILY COSTS

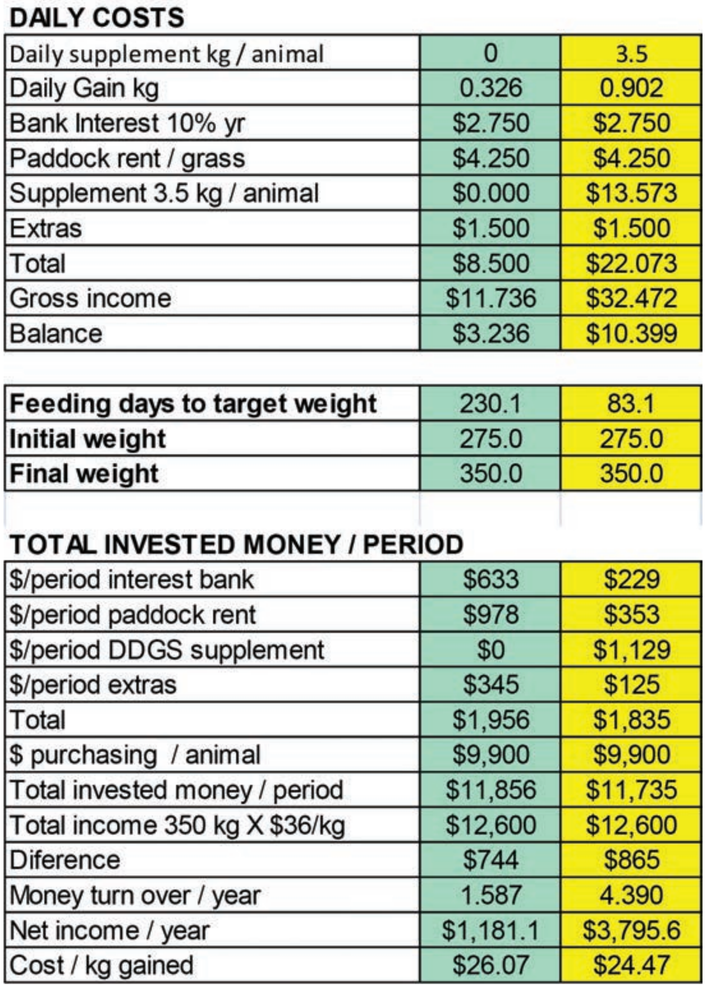
Daily supplement kg / animal	0	3.5
Daily Gain kg	0.138	0.791
Bank Interest 10% yr	$2.186	$2.186
Paddock rent / grass	$4.250	$4.250
Supplement 3.5 kg / animal	$0.000	$13.573
Extras	$1.500	$1.500
Total	$7.936	$21.509
Gross income	$4.968	$28.476
Balance	-$2.968	$6.967

Feeding days to target weight	952.2	166.1
Initial weight	218.6	218.6
Final weight	350.0	350.0

TOTAL INVESTED MONEY / PERIOD

$/period interest bank	$2,081	$363
$/period paddock rent	$4,047	$706
$/period DDGS supplement	$0	$2,255
$/period extras	$1,428	$249
Total	$7,556	$3,573
$ purchasing / animal	$7,870	$7,870
Total invested money / period	$15,426	$11,443
Total income 350 kg X $36/kg	$12,600	$12,600
Diference	-$2,826	$1,157
Money turn over / year	0.383	2.197
Net income / year	-$1,083.3	$2,543.0
Cost / kg gained	$57.51	$27.19

Table 7. Economic cost summary of the heavy weight heifer group



DAILY COSTS

Daily supplement kg / animal	0	3.5
Daily Gain kg	0.326	0.902
Bank Interest 10% yr	$2.750	$2.750
Paddock rent / grass	$4.250	$4.250
Supplement 3.5 kg / animal	$0.000	$13.573
Extras	$1.500	$1.500
Total	$8.500	$22.073
Gross income	$11.736	$32.472
Balance	$3.236	$10.399

Feeding days to target weight	230.1	83.1
Initial weight	275.0	275.0
Final weight	350.0	350.0

TOTAL INVESTED MONEY / PERIOD

$/period interest bank	$633	$229
$/period paddock rent	$978	$353
$/period DDGS supplement	$0	$1,129
$/period extras	$345	$125
Total	$1,956	$1,835
$ purchasing / animal	$9,900	$9,900
Total invested money / period	$11,856	$11,735
Total income 350 kg X $36/kg	$12,600	$12,600
Diference	$744	$865
Money turn over / year	1.587	4.390
Net income / year	$1,181.1	$3,795.6
Cost / kg gained	$26.07	$24.47

during the year. Along the 850 kg, it can be divided into three sections: North, Central and South, with each section differing in latitude and weather conditions.

The north region is dryer and cold compared with the other two regions, which allows the beef and milk producers to use cross breed cebu X European breeds like Charolais, Angus, Montbeliade, Simmental, Braunvieh, European Swiss, etc. These types of animals are preferred by the feedlots. The favorable weather conditions for the European type beef also are against the forage production; the grass paddocks usually produce limited amounts of low digestible forages. The net result of these combinations are high genetic merit of the animals with a low plane of nutrition, which leads to different undesirable conditions, such as low daily gains, reduced milk production and failure to breed the cows every year.

In this first attempt to work with the beef and milk producers from the north of Veracruz promoting the use of DDGS, DDGS was not used as a concentrate, but was blended with digestible forage due to the low availability and indigestibility of forages from the grass pastures. If the animals were not capable of maximizing dry matter intake, almost any concentrate will be insufficient to show the genetic potential of these animals. January to May is the dry and cold season, with a lack of good forages, and the price paid for the calves less than 230 kg is the highest compared with heavier animals.

Therefore, a producer from Ozuluama Veracruz was asked to conduct a DDGS field demonstration. A total of 32 animals were sorted into two groups with an initial average body weight of 99.8 kg each group. Group 1 (Potrero) received the traditional feeding practices and management and group 2 (DDGS) received the high DDGS ration in a 100 percent confinement with ad libitum access to water. Each group consisted of nine heifers and seven young bulls Table 1. Diet formulations are shown in Table 2 and feeding practices are shown in Table 3. Animals from Group 1 were allocated on grass paddocks and offered some commercial concentrate 1.0 kg plus some fresh citrus pulp, once a day. One additional benefit for Group 1 animals, these animals have more square meter of grass every day, since 13 animals were placed in 100 percent confinement. During the first weeks after the start of the demonstration, three animals from each group were

Table 1. Distribution of sex and body weight between the two experimental groups

Rancho Paisaje, Ozuluama Veracruz February 23, 2017

Group	Sex	ID Number	kg	Group	Sex	ID Number	kg
1	female	3740	70	2	female	3715	75
1	female	3729	83	2	female	3724	80
1	female	3747	95	2	female	3741	94
1	female	8301	97	2	female	3728	98
1	female	3726	98	2	female	8299	100
1	female	3745	107	2	female	3730	107
1	female	3717	109	2	female	8303	108
1	female	3718	110	2	female	8353	112
1	female	3723	147	2	female	3720	124
1	male	5347	50	2	male	8319	64
1	male	3739	88	2	male	3738	71
1	male	3742	90	2	male	3744	90
1	male	3791	93	2	male	3746	100
1	male	3725	104	2	male	8307	114
1	male	8356	116	2	male	3716	123
1	male	8311	139	2	male	3727	136
		kg Total	1,596			kg Total	1,596
16		kg average	99.75	16		kg average	99.75

Table 2. Diet formulation of DDGS calf starter (18 percent crude protein) and ration for Group 2

Ingredient	kg / MT
Calf Starter (18% Crude Protein)	
DDGS	480
Ground yellow corn	300
Sugarcane molasses	100
Corn pericarp	90
Vitamin & mineral premix	30
Total	1,000
Ration	
Calf Starter	680
Chopped grass hay	230
Sugarcane molasses	90
Total	1,000

Table 3. Feeding practices

From	23 Feb 17	28 Mar 17	27 Apr 17	24 May 17
Until	28 Mar 17	27 Apr 17	24 May 17	26 Jun 17
kg ration / day / animal	3.5	4.5	5.5	6.5
Concentrate	2.39	3.07	3.75	4.43
Chopped grass hay	0.80	1.02	1.25	1.48
Sugarcane molasses	0.32	0.41	0.50	0.59

removed and kept under different management conditions. During the first 33 days, approximately 10 days were used to adapt the Group 2 animals to the 100 percent confinement. However, the group fed DDGS showed a better performance and we began to calculate the number of days needed to reach the desire body weight, considering the average daily gain (kg). The number of males and females in each group remain constant for the entire demonstration and the growth rates of remaining cattle in each group are shown in Table 4.

Approximately every 30 days, all the animals (group 1 and 2) were individually weighed and weight were recorded. After the fourth test weight (May 24), several animals from group 2 were very close to the 230 kg and it was decided to sell them before they exceeded 230 kg live weight. Once these cattle were sold, the extra young animals were added to take their place along with 13 of the original animals from group 1 until June 26. Figure 1 shows the average body weight, Figure 2 shows the kilogram gained, and Figure 3 shows the average daily gain for each dietary treatment. Results from this study show the benefits of feeding high amounts of DDGS combined with forage to improve average daily gain (in kg) over the control group fed no DDGS. Furthermore, the cost of production is also reduced by feeding DDGS.

Every day, the animals in the DDGS treatment (group 2) required an extra investment, but the daily net income was greater for this group with $11.21 Mx pesos per animal. All the ranches have the goal of producing more liters of milk liters or kg of beef in the least amount of time. According to the traditional management, these animals (Group 1) would require approximately 206 days to reach 230 kg and the Group 2, almost 100 days (not considering the animals that finished earlier). It is important to note that the number of turnovers of the money per year. Every time an animal is sold, regardless of which treatment group, the farmer will realize a positive difference of $2,700 Mx pesos from Group 1 compared with the $2,408 from Group 2. Although most producers believe that it may be more economical to not feed extra supplement, the data from this trial clearly show that these positive economic benefits can be realized only 1.77 times per year for Group 1 animals, compared with 3.77 times per year from Group 2 animals. Therefore, every year, the animals from group 1 generate $4,769.1 Mx pesos compared with $8,860.8 from animals of Group 2. Not only is the daily gain (kg) important, but also is the time involved in reaching desired body weights in commercial beef production systems.

Table 4. Growth rate of cattle during the second weigh period

Rancho El Paisaje									
			Days interv	33					
		Weight test	23-feb-17	28-mar-17					
			kg	kg	kg gained	ADG kg	Days to 230 kg	Male	Female
Control group		Average 1	105.0	124.7	19.7	0.597	176.5	4	9
DDGS group		**Average 2**	**105.7**	**135.7**	30.0	0.909	103.7	5	8

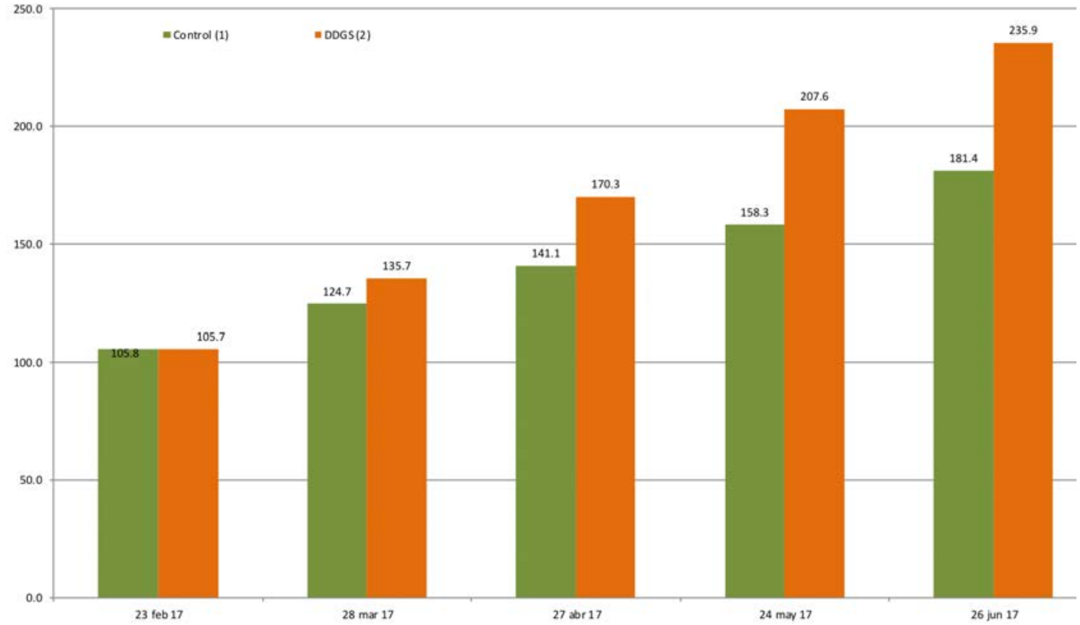


Figure 1. Effect of dietary treatment on cattle body weight throughout the feeding period

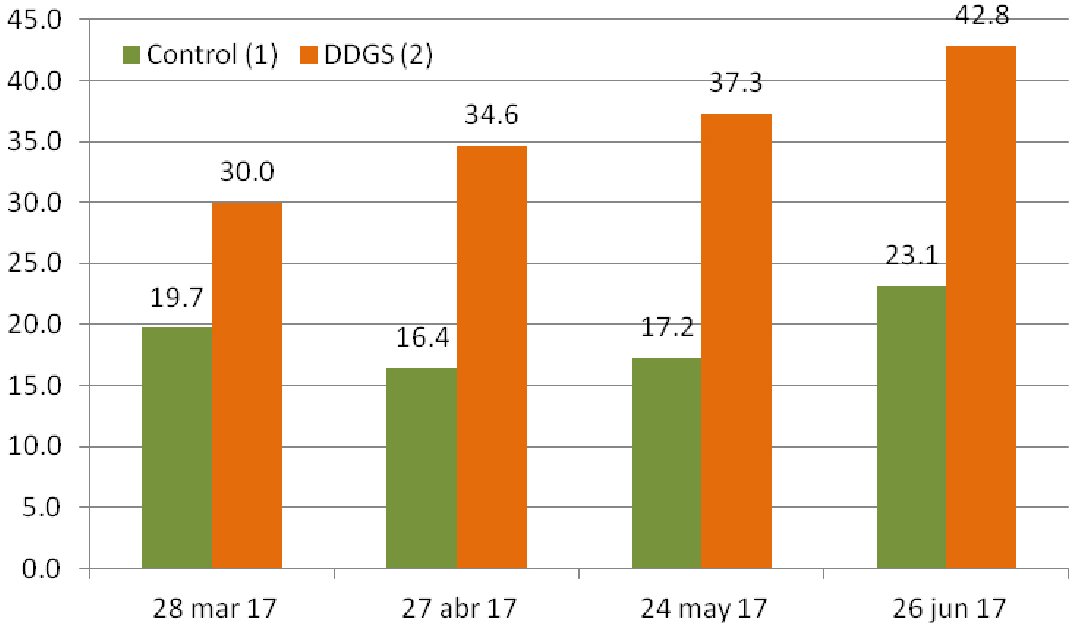


Figure 2. Effect of dietary treatment on cattle body weight gain (kg) throughout the feeding period

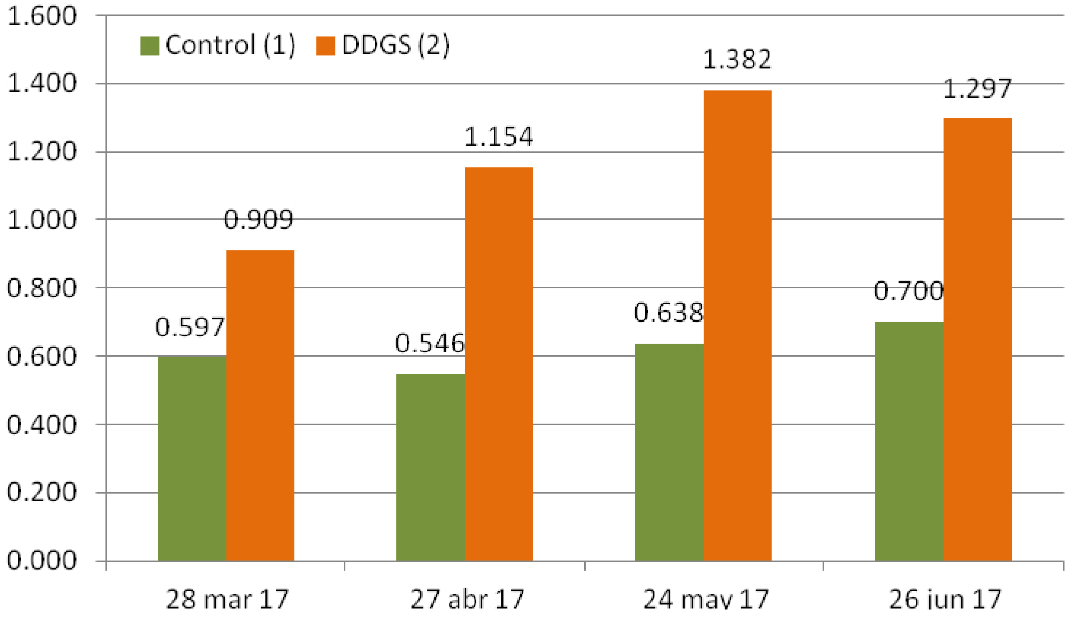


Figure 3. Effect of dietary treatment on cattle average daily gain (kg) throughout the feeding period

TRIAL 4

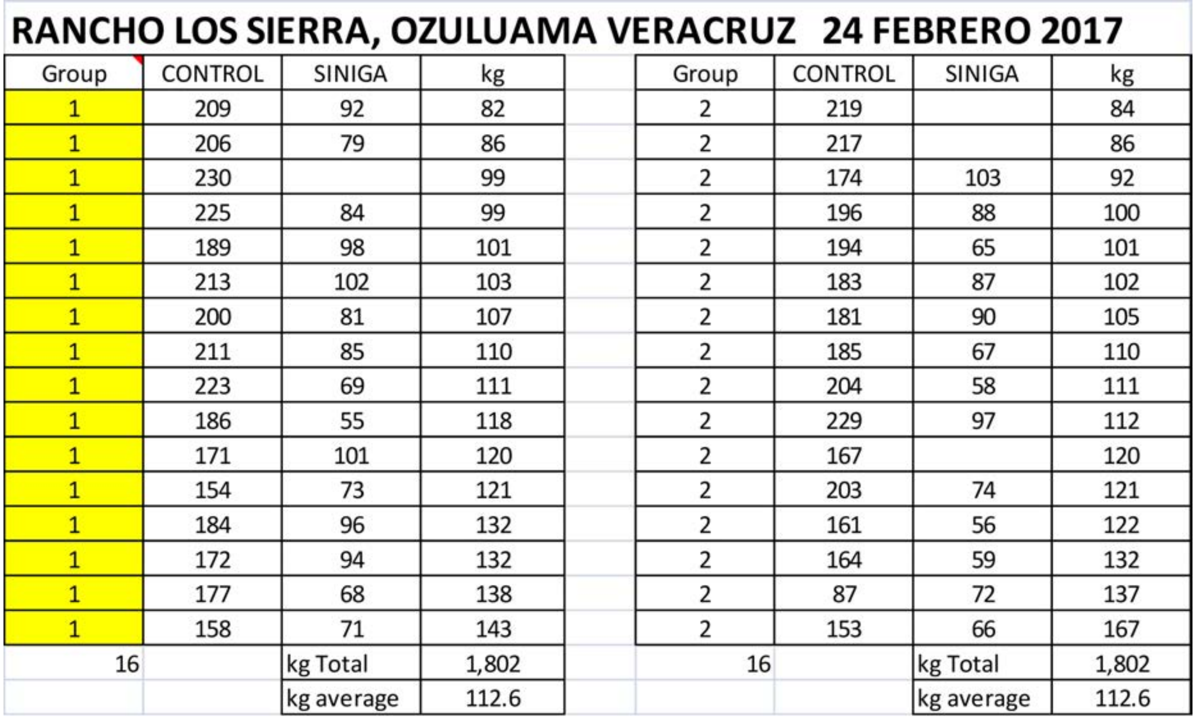
USGC DDGS field demonstration in Ozuluama Veracruz from February 24 to June 27, 2017 at Los Sierra ranch

The Veracruz state is almost 850 km long (528 miles) surrounding the Gulf of Mexico. On the west side of the state is located the Sierra Madre Oriental, and the Mexican Gulf shore is on the east side of the state. This geographic location allows the Veracruz state to receive large amounts of rainfall during the year, but along the 850 km, the state can be divided into the north, central and south regions which differ in latitude and weather conditions. The north region is dryer and colder compared with the other two regions, and these weather conditions allows the beef and milk producers to use cross breed Cebu × European breeds like Charolais, Angus, Montbeliarde, Simmental, Braunvieh European Swiss, etc., which are preferred by the feedlots. However, the favorable weather conditions for raising the European type beef breeds do not match forage production capabilities because the grass pastures usually produce limited amounts of low digestible forages. The net result of this combination is high genetic merit of the animals but they are provided a low plane of nutrition. As a result, several undesirable effects occur such as low daily gains, reduced milk production and low pregnancy rates of cows every year.

In this first attempt to work with the beef and milk producers from the north of Veracruz, the Council promoted the use of DDGS not as a single concentrate, but to blend with digestible forage due to the low availability and indigestibility of forages from the pastures. If the animals are not able to maximize dry matter intake, almost any concentrate will be insufficient to allow the genetic potential of these animals to be maximized. During the months from January to May, the dry and cold season occurs with the lack of good forages, and the price paid for the calves less than 230 kg is the greatest compared with heavier animals.

At the Los Sierra ranch, about 60 cows are milked once daily and the milk is sold to a local cheese plant. The owners of this ranch also raise yearling bulls on grass pastures. Depending on live weight price paid for the yearling bulls, the decision to sell them is based on when the animals reach 350 kg or 400 kg in body weight. In this demonstration study, several groups of young bulls with average body weights of 100, 150, 200, 250, 300 and 350 kg. Therefore, the trial was conducted to compare feeding the current concentrate (Dulce 20) being used with a DDGS concentrate. The feeding program at this ranch consists of offering an amount of commercial concentrate equivalent to 1 percent of body weight, where calves weighing an average of 100 kg receive 1 kg of concentrate and cattle weighing an average of 350 kg receive 3.5 kg of concentrate, when digestible forage is available in the grass pastures. This extra concentrate is known as "taco." A total of 32 bulls were divided into two groups with 16 bulls each and an average body weight of 112 kg, where Group 1 was fed DDGS and Group 2 was fed the current Dulce 20 concentrate. Table 1 shows the initial number of animals and average body weight by group.

Table 1. Initial number of bulls and body weight used in the feeding trial



RANCHO LOS SIERRA, OZULUAMA VERACRUZ 24 FEBRERO 2017

Group	CONTROL	SINIGA	kg		Group	CONTROL	SINIGA	kg
1	209	92	82		2	219		84
1	206	79	86		2	217		86
1	230		99		2	174	103	92
1	225	84	99		2	196	88	100
1	189	98	101		2	194	65	101
1	213	102	103		2	183	87	102
1	200	81	107		2	181	90	105
1	211	85	110		2	185	67	110
1	223	69	111		2	204	58	111
1	186	55	118		2	229	97	112
1	171	101	120		2	167		120
1	154	73	121		2	203	74	121
1	184	96	132		2	161	56	122
1	172	94	132		2	164	59	132
1	177	68	138		2	87	72	137
1	158	71	143		2	153	66	167
16		kg Total	1,802		16		kg Total	1,802
		kg average	112.6				kg average	112.6

The feeding trial began on February 24, 2017, when both groups were provided separate grass pastures with portable bunk feeders and ad libitum access to water. Every morning the animals received 2 kg of concentrate plus 1 kg of chopped hay, and the remainder of the day they had access to the grass pastures. At the end of each month the 32 cattle were moved to the holding pen to obtain body weights.

Initial body weight of both groups was 113 kg. At the end of the first month of the trial, the cattle in both groups had similar body weights (136 kg for those fed DDGS and 135 kg for those fed the commercial supplement). However, after feeding these concentrates for the second month, cattle fed the DDGS diet had greater body weight (152 kg), average daily gain (0.57 kg/day) and were projected to reach 230 kg in 138 days. The cattle in the control group had average body weight of 147 kg, average daily gain of 0.38 kg/day, and were projected to reach 230 kg in 218 days. However, growth rates were less than desired for both groups because of limited forage intake from the grass pastures during this time of the year. The cattle continued to be fed these same diets for the next month (May) and growth rates of the bulls did not improve from the previous month (0.58 kg/day for DDGS and 0.31 kg/day for control). After consulting with the owner, it was agreed to adopt a 100 percent confinement system and feed the cattle a diet consisting of 680 kg DDGS concentrate, 230 kg grass chopped hay and 90 kg of Sugarcane molasses. The bulls remained on the grass pastures, but it was recommended that they be fed 4 kg of the mixture per animal per day to improve nutrient intake and growth rate of these animals. Unfortunately, the cattle continued on the previous feeding program because the change in feeding program was not communicated to emplyees responsible for feeding the cattle. However, the final results showed a positive benefits of feeding the DDGS concentrate on body weight gains increased and days to reach 230 kg in body weight were reduced by 10 days. A summary of cattle body weights, body weight gain, and average daily gain are summarized in Figure 1, 2 and 3, respectively.

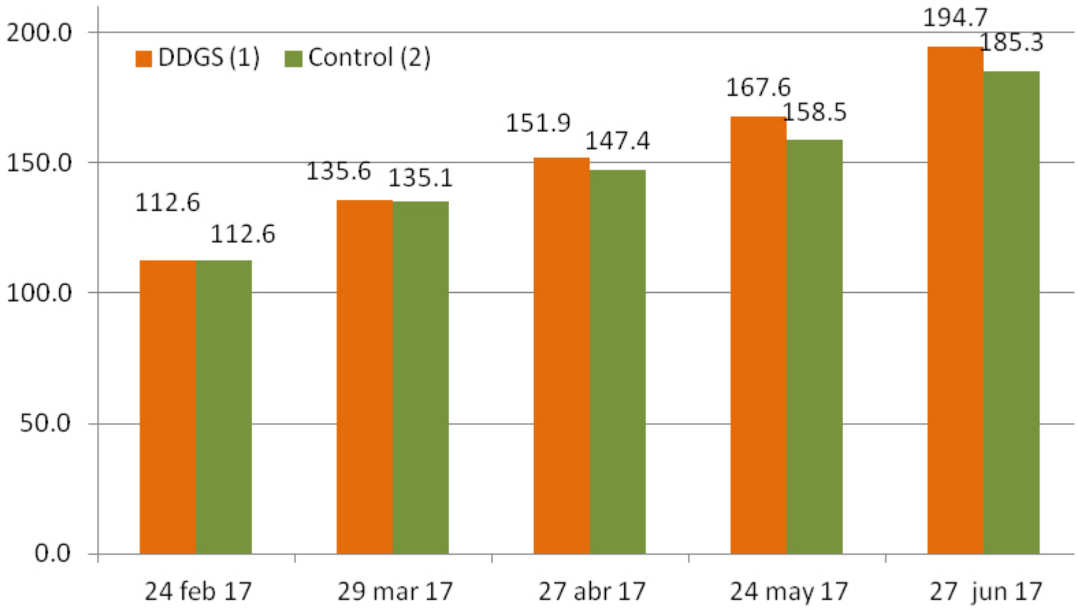


Figure 1. Comparison of average body weights of cattle fed DDGS vs control supplements over a five–month feeding period

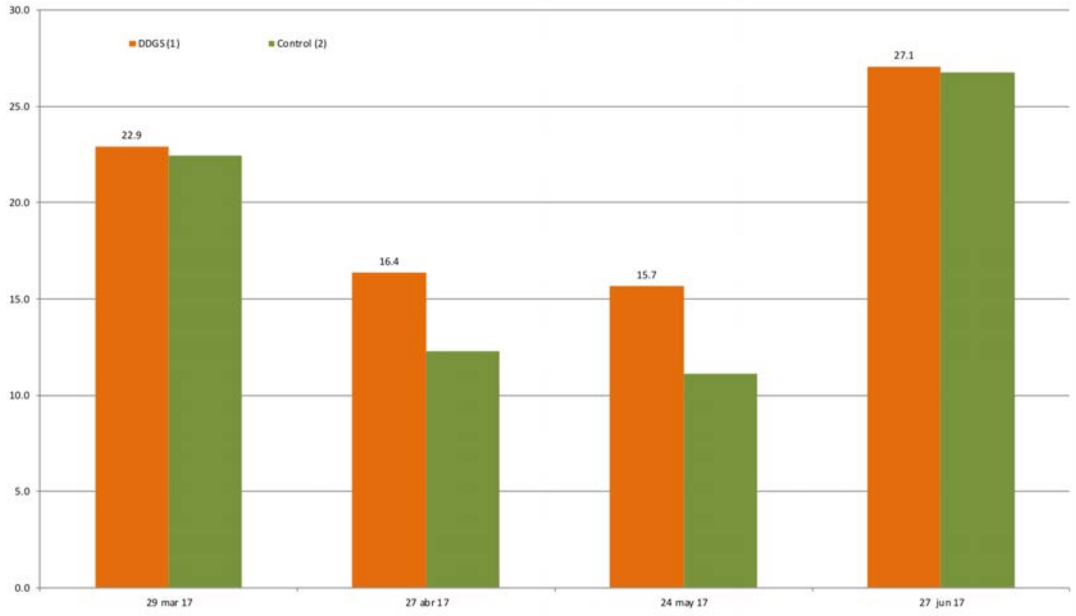


Figure 2. Comparison of average body weight gain of cattle fed DDGS vs control supplements over a five–month feeding period

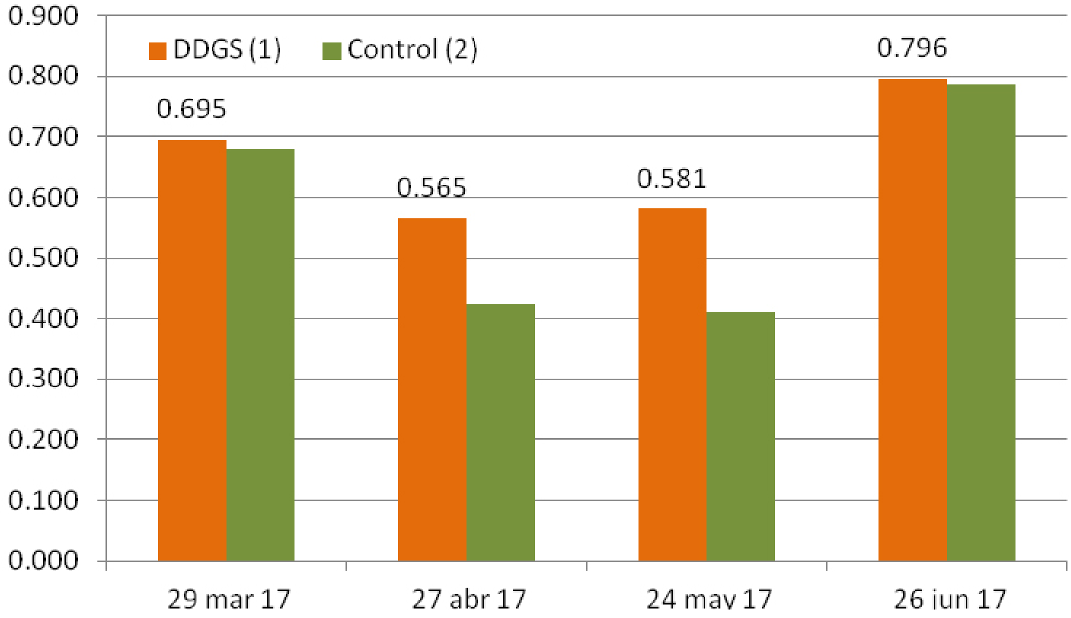


Figure 3. Comparison of average daily gain of cattle fed DDGS vs control supplements over a five–month feeding period

In this field demonstration trial, the same feeding practices were compared using with two types of concentrates, one with high levels of DDGS and a second one a commercial formula known as Dulce 20. The Dulce concentrate costs $8.00 Mx pesos/kg compared with $6.75 Mx pesos for the DDGS concentrate (Table 2). For these young bulls fed 3 kg of ration, which consist of 2 kg of concentrate and 1 kg of grass chopped hay, the cost of feeding the Dulce 20 Ration every day was $16.50 Mx pesos/animal compared with $14.00 Mx pesos/animal when feeding the DDGS ration.

After the 123 days feeding period, cattle fed the high DDGS concentrate had increased average daily gain and more kilogram gained during the period, which represents an important savings time and money. In addition, each animal from Group 1 (DDGS) generate a positive balance of $10.129 Mx pesos per day compared with the $4.010 Mx pesos from Group 2 (Table 3). Although the young bulls in this demonstration did not gain more than 0.80 kg per day compared with 1.3 kg per day from other demonstration trials in Mexico with the same weight, bulls fed the DDGS concentrated in this trial showed an economic benefit of about $1,000 Mx pesos per bull during the entire period of time compared with Group 2. In fact, the cost of kilogram gained was almost $8.2 Mx pesos per kilogram less compared with the cost from Group 2. In conclusion,

Table 2. Comparison of feed cost/animal/day when feeding a commercial concentrate or DDGS concentrate

Ration Dulce 20	kg /an / day	$ / kg	Cost
Concentrate	2	$8.00	$16.00
Chpped grass hay	1	$0.50	$0.50
Total cost	3		$16.50
		kg =	$5.50

Ration high DDGS	kg /an / day	$ / kg	Cost
Concentrate	2	$6.75	$13.50
Chpped grass hay	1	$0.50	$0.50
Total cost	3		$14.00
		kg =	$4.67

Table 3. Cost comparison of feeding a commercial supplement or a high DDGS supplement for the Los Sierra Ranch

	DDGS	Commercial
DAILY COSTS	Group 1	Group 2
Daily supplement kg / animal	3	3
Daily Gain kg	0.667	0.590
Bank Interest 10% yr	$1.470	$1.470
Paddock rent / grass	$4.250	$4.250
Supplement 3 kg / animal	$14.000	$16.500
Extras	$1.500	$1.500
Total	$21.220	$23.720
Gross income	$31.349	$27.730
Balance	$10.129	$4.010

Feeding days to target weight	176.0	199.0
Initial weight	112.6	112.6
Final weight	230.0	230.0

TOTAL INVESTED MONEY / PERIOD		
$/period interest bank	$259	$293
$/period paddock rent	$748	$846
$/period DDGS supplement	$2,464	$3,283
$/period extras	$264	$298
Total	$3,735	$4,720
$ purchasing / animal	$5,292	$5,292
Total invested money / period	$9,027	$10,012
Total income 230 kg X $47/kg	$10,810	$10,810
Diference	$1,783	$798
Money turn over / year	2.074	1.834
Net income / year	$3,697.1	$1,463.6
Cost / kg gained	$31.81	$40.20

the genetic background from the bulls on this ranch can support a greater average daily gains if the farmer decides not to limit feed intake and provides sufficient nutrition to meet their daily requirements.

TRIAL 5

A beef cattle feeding trial was conducted in 2016 on the San Francisco ranch near Tizimin, Yucatan. Yucatán´s cattle production is mostly in the municipalities located to the east part of Yucatán´s Peninsula (Tizimín, Buctzotz, Panaba, Sucila), and cattle production systems in the state are extensive. Animals graze on native or induced pastures. Generally, supplements are only used during the dry season to scarcely meet maintenance requirements of the animals. Poultry litter is the main component of these feeds. A great majority of ranchers consider supplementation as a cost and not as an investment. Therefore, on traditional Yucatán farms, the average daily gain of cattle is between 400 and 600 grams per day. Reproductive results of traditional breeding herds are also below the optimal performance expected for this area and breeds. In general, Yucatán ranchers are conservative and rarely change their production practices, despite their poor results. However, farmers tend to look at one another to decide what to buy. They feel safe and reassured if another rancher buys a new product, particularly, if the buyer is leader of opinion among cattle producers.

Mr. Pedro Couoh is a well-known rancher among Yucatán producers, both for his excellent purebred Swiss herd and F1 crosses. Therefore, a feed demonstration at Mr. Pedro Couoh´s ranch (San Francisco) was conducted. Due to results the trial will have a positive impact on other regional cattle producers. In addition, the DDGS group will participate at Xtmakuil Livestock Fair, one of the most important Cattle Shows southeast Mexico.

Ranch Description:
Rancho San Francisco is located in the municipality of Tizimín, Yucatán The climate of the region is tropical sub-humid with monthly temperature and annual rainfall averages of 26 C and 1100 mm respectively. The ranch produces purebred Brown Swiss and F1 hybrid cattle.

Couoh uses a semi-intensive method of rearing. At night, animals graze on Mulato – 2 (Brachiaria ruziziensis), Brizantha (Brachiaria brizantha) and Tanzania (Panicum maximum) grasses and during the day, when temperatures tends to rise, animals are kept in free stall barns, where they are supplemented and have access to fresh water.

Facilities are well maintained and clean. The ranch has a digital scale to weigh the cattle. Unlike other ranches of the region, production records are kept. The ranch follows a preventive veterinary health program specific for this region.

Material And Methods:
Twenty-four Brown Swiss (BS) purebred and crossbred animals were assigned to two treatment groups (DDGS and control) to evaluate the effect of DDGS on the rate of gain of the cattle. Each group consisted of six bulls and six heifers. Initial body weights of the DDGS and of the control groups were 305 and 297 kg, respectively. DDGS group final weight was 366 kg, while final weight of the control group was 348 kg. The animals were weighted individually each 15 days. Eartags were used to identify each animal and keep accurate records for average daily gain (ADG). Trial duration was 75 days from July to October 2016.

The animals received two different diets. The control diet consisted of 3 kg commercial feed (16 percent crude protein content) and 3 kg of a mix of 70 percent poultry litter and 30 percent corn ("Productor Plus") per head per day (Table 1). The DDGS diet consisted of 3 kg supplement (85.47 percent DDGS/12.82 percent molasses/ 1.71 percent mineral premix) and 3 kg Productor Plus per head per day (Table 2). Total feed cost per head for the 75 day trial was Mx $1946.45 and Mx $1991.25, for the DDGS group and for the Control group, respectively. Table 3 shows DDGS supplement composition. The poultry litter mixture composition is shown in Table 4. Each group was supplemented separately during the day and at night both groups grazed on Mulato – 2 (Brachiaria ruziziensis), Brizantha (Brachiaria brizantha) and Tanzania (Panicum maximum) grasses.

Results:
Because each 15 days animals were weighed, performance results are presented according to the five periods in which the trial was divided (five weighing dates). ADG is presented for each of these periods as well the accumulated ADG of the whole trial and by also by sex. The overall ADG for the DDGS group was greater 1 kg greater than that of the control group (0.84 kg). Nevertheless, rate of gain was not uniform, but both groups showed similar tendency (Figure 1), except at the fourth period, when the rate of gain of the DDGS animals presented a light decrease, but it recovered in the following period, but not for the control group, which ADG markedly decreased at the end of the trial. Compared ADG of both groups is presented in Figure 2.

ADG of bulls in the DDGS treatment was 1.42 kg/day, whereas ADG of bulls of the control group was 1.07 kg/day. In both cases, performance was not uniform. Over the entire trial, ADG of the DDGS group shows two decreases (second and fourth), but it markedly increased at the end of the trial. The control group showed similar tendency (Figure 3), except in the last two periods, when ADG substantially decreased. The ADG of both groups is presented in Figure 4.

Table 1. Control diet

Ingredient	Cost/kg Mx	kg/head/day	Cost/day, Mx
Commercial feed 16%	$6.10	3.0	$18.30
Productor Plus	$2.75	3.0	$ 8.25

Table 2. DDGS diet

Ingredient	Cost/kg Mx	kg/head/day	Cost/day Mx
DDGS supplement	$5.90	3.0	$17.70
Productor Plus	$2.75	3.0	$ 8.25

Table 3. DDGS supplement formula

Ingredient	percent
DDGS	85.47
Molasses	12.82
Mineral premix	1.71
Total	100

Table 4. Poultry litter mixture (Productor Plus)

Ingredient	percent
Poultry litter	70
Corn	30
Total	100

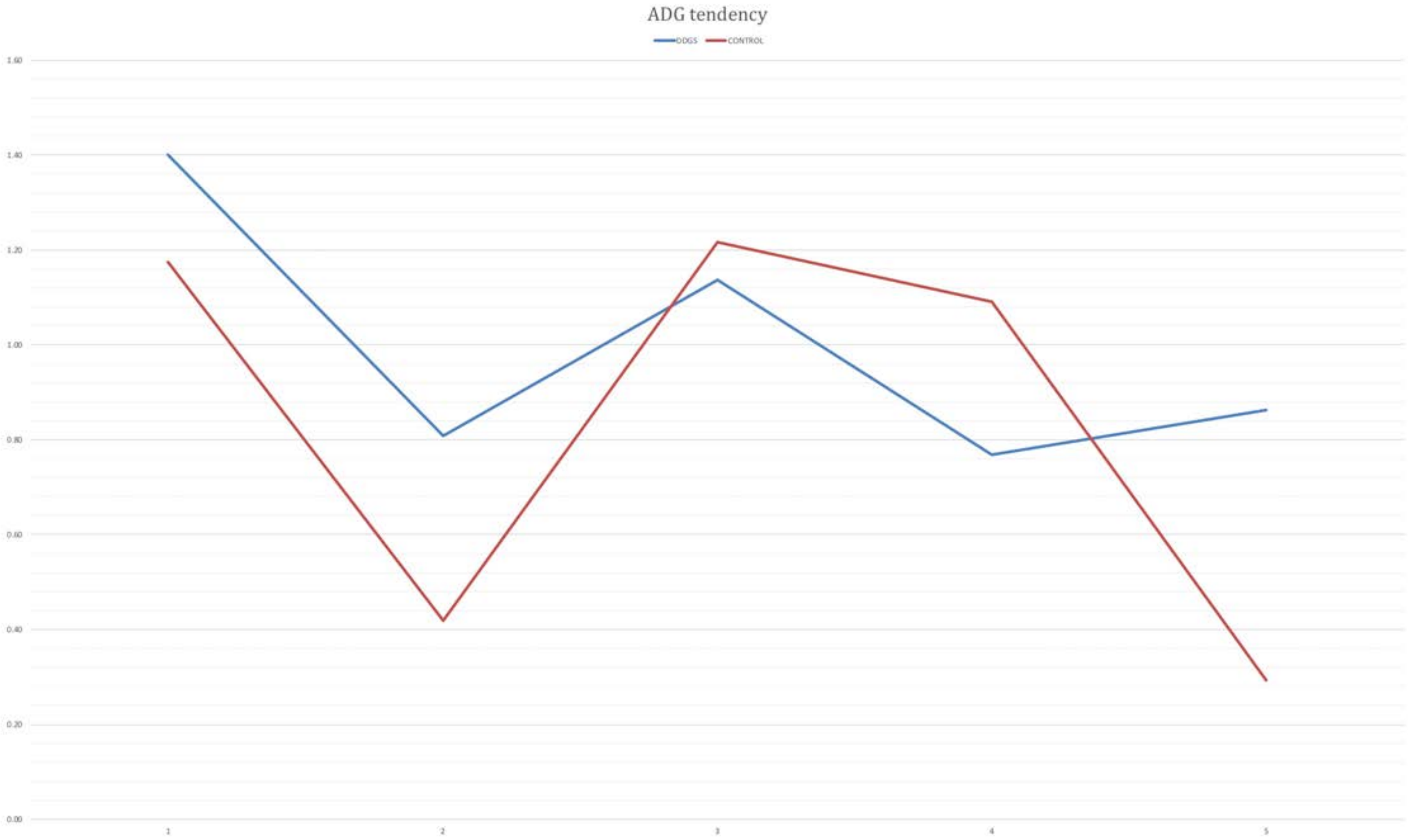


Figure 1. Variation in ADG of cattle fed the control and DDGS and Productor Plus during the trial

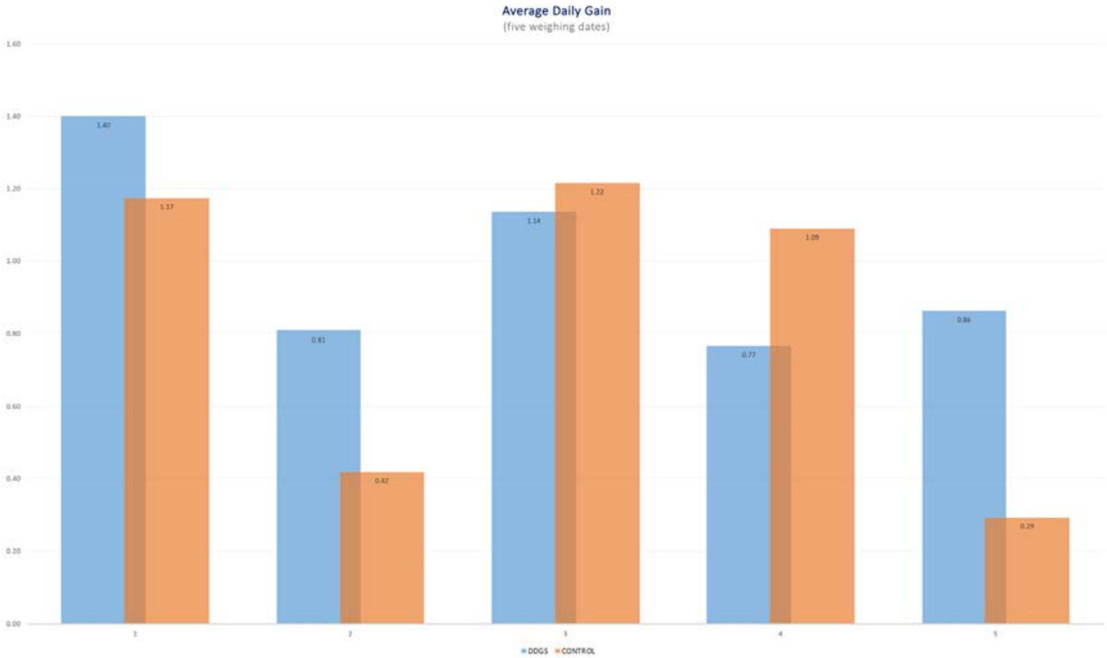


Figure 2. Average daily gain of both groups at various times during the entire trial

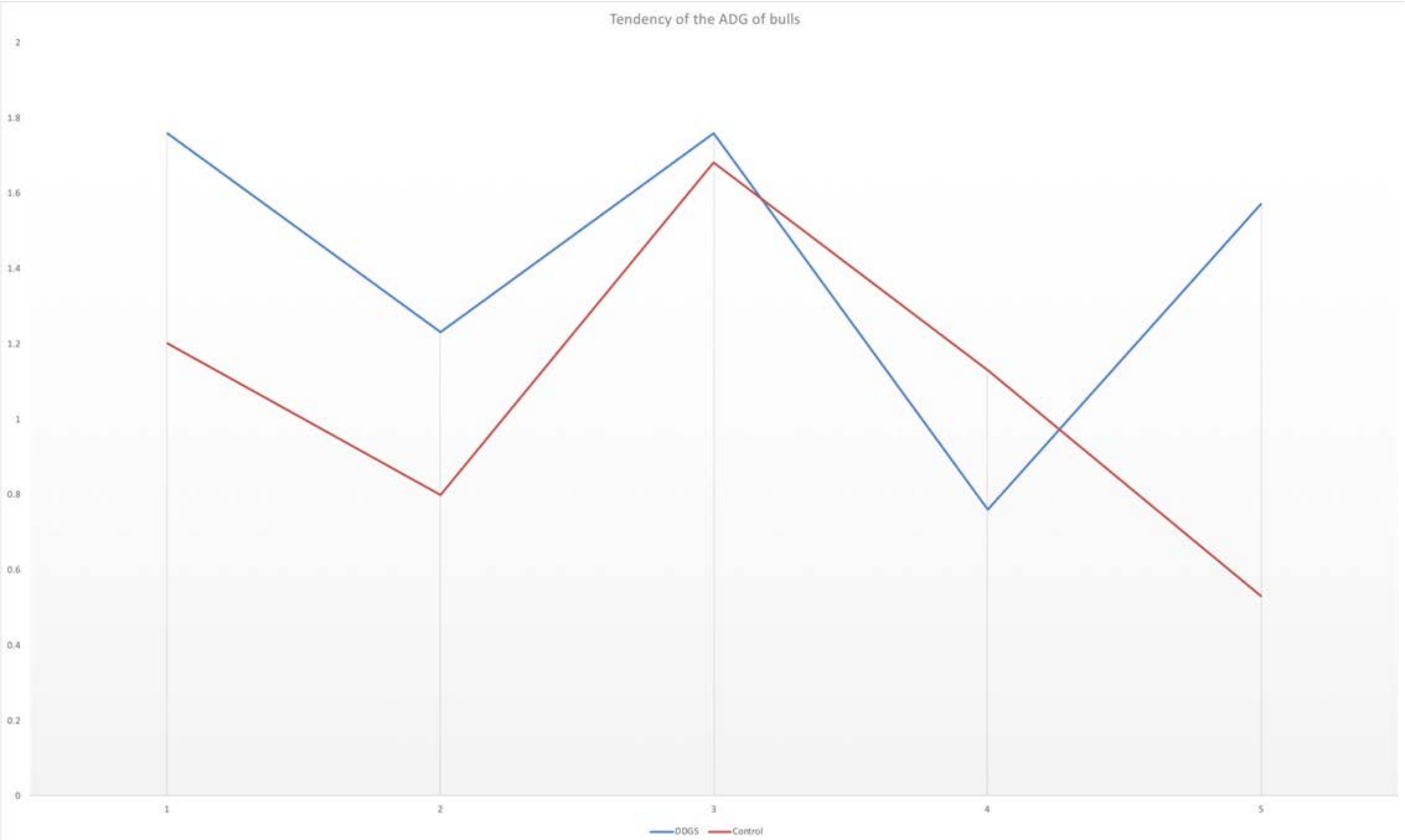


Figure 3. Variation in ADG of cattle fed the control and DDGS and Productor Plus during the trial

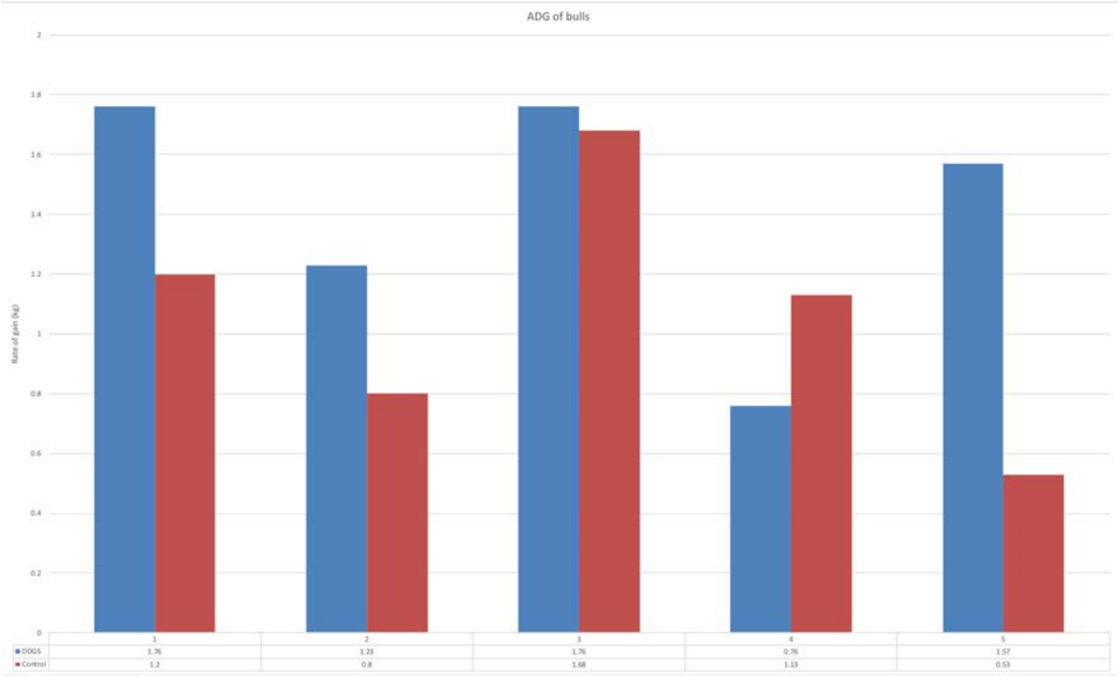


Figure 4. ADG of bulls of both groups

Accumulated ADG of heifers of the DDGS treatment was 1.08 kg/day, whereas ADG of heifers of the control group was 1.02 kg/day. In both cases, performance was not uniform over the trial, where ADG of the DDGS group shows two decreases (second and fourth), but it markedly increased at the end of the trial. The control group showed similar tendency, except in the last two periods, when ADG substantially decreased. ADG of both groups is presented in Figure 5.

Bull fertility test

Because these animals will be sold for breeding, performing a fertility test prior to sale was important to guarantee customers the fertility of the bulls as potential breeders. Examination of internal and external genitalia, as well as collection and evaluation of semen of all males was performed. Both group of animals presented normal genitalia, and results of the qualitative and quantitative evaluation of semen were also normal.

Animal coat and general appearance of the animals

The owner commented that the coat and general appearance of the animals of the DDGS group was better than the Control group.

Economic Analysis

The cost per kilogram of body weight gain was calculated considering total feeding costs for the entire trial, as well as body weight increase of both groups. In the case of the DDGS group, the cost per kilogram of body weight gain, was Mx $31.91, or 18 percent less than the control group, which cost had a cost of Mx $39.04/kg body weight gain (Table 5).

Conclusions

1. The ADG of animals receiving a diet with DDGS was greater than the ADG of the control group that were fed a common commercial supplement.

2. DDGS can be effectively used to feed animals raised under extensive and semi-intensive systems, under Yucatán´s climatic conditions.

3. DDGS is a cost effective ingredient for typical cattle diets, used in Yucatán.

4. Feeding DDGS does not affect fertility of young bulls.

5. Feeding DDGS appears to improve cattle hair coat.

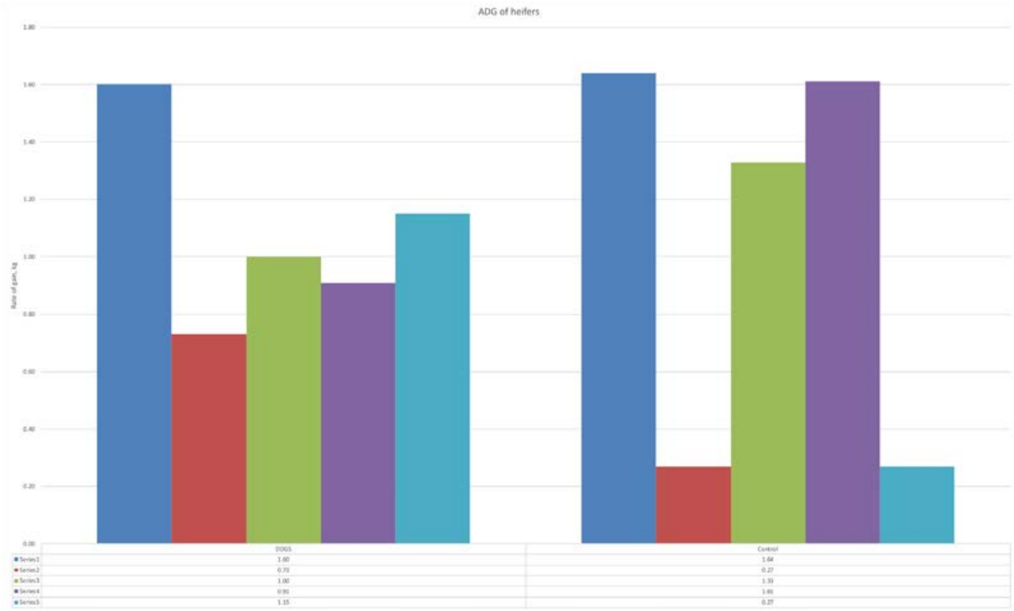


Figure 5. Average daily gain of heifers in both dietary treatment groups Note: each series corresponds to a weighing period.

Table 5. Cost/kg of body weight gain

	DDGS	Control
Initial weight, kg	305	297
Final weight, kg	366	348
Difference, kg	61	51
Total feed cost/trial	$1,946.45	$1,991.25
Cost/kg gained	$ 31.91	$ 39.04

Dairy Cattle

TRIAL 1

A lactating dairy cow feeding trial was conducted in Francisco Gaytan, Huimanguillo Tabasco, Mexico to compare milk production among two groups of cows with similar days in milk and milk production. A total of 34 cows (less than 105 days in lactation) were used and allotted to one of two feeding groups where they were fed 2 kg/cow/day of either a regular commercial concentrate (n = 17 cows) and the second group was fed a DDGS supplement (n = 17 cows). The supplement formulation is shown in Table 4. The supplement formulation is shown in Table 1. According to the information provided by the owner, the cost of the commercial concentrate was $5.00 Mx pesos/kg and the DDGS supplement was $5.76 Mx pesos/kg. The milk produced was delivered to a local cheese plant and the price paid was $5.20 Mx pesos/liter, and the milk was tested individually every 14 days.

Results from this trial are shown in Figure 1 and 2. Cows fed the DDGS supplement and were less than 50 days in milk (DIM) produced 2.88 more liters/day of milk than cows fed the commercial supplement (Figure 1). These results suggest that greater improvements in milk production may be achieved by feeding the DDGS supplement when cows reach peak milk production. As shown in Figure 5, cows fed the DDGS supplement produced 2.77 more liters of milk, and this increase became greater by the end of the feeding trial.

Table 1. DDGS supplement formulation

Ingredient	kg / MT
Grass hay	100.0
DDGS	559.2
Sugarcane molasses	111.4
Ground yellow corn	155.9
Urea	17.8
Mineral Premix	55.7
Total	1,000.0

The higher cost of the DDGS supplement is often not accepted by most milk producers in Mexico because they want to buy inexpensive concentrates that produce a lot of milk. During this demonstration it was evident that the commercial concentrates do not support a higher milk production, which limits the potential milk production. As shown in Table 2, cows fed the DDGS supplement had $1.52 greater feed cost/day than those fed the commercial supplement. However, as shown in Table 3, cows fed the DDGS supplement produced more milk which resulted in greater gross and net income than cows fed the commercial supplement. These results convinced the owner that even though the DDGS supplement was higher in cost, it also resulted in greater milk production. As a result, the owner has decided to start producing and selling the supplement in her town.

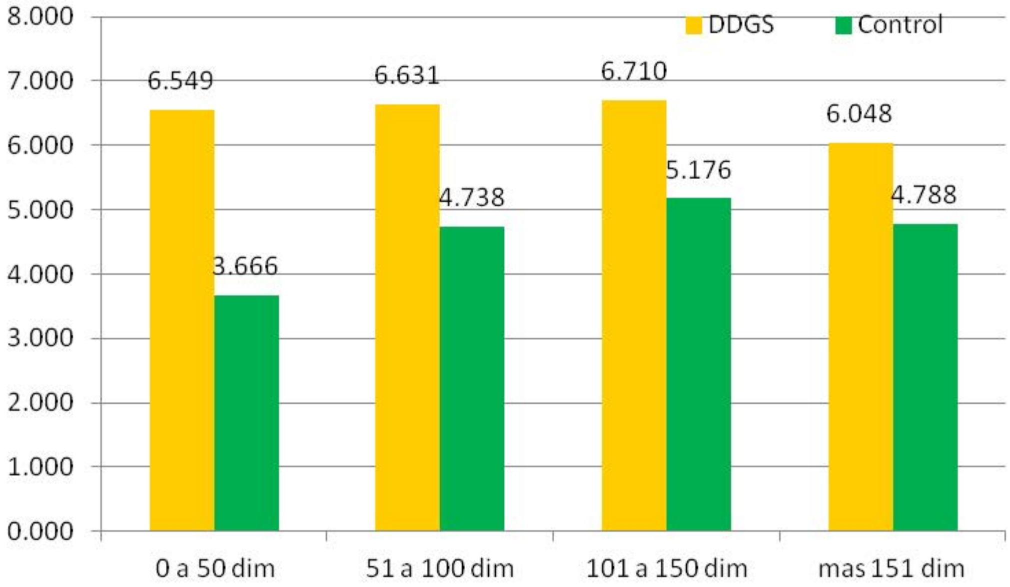


Figure 1. Average milk production (liters) by days in milk

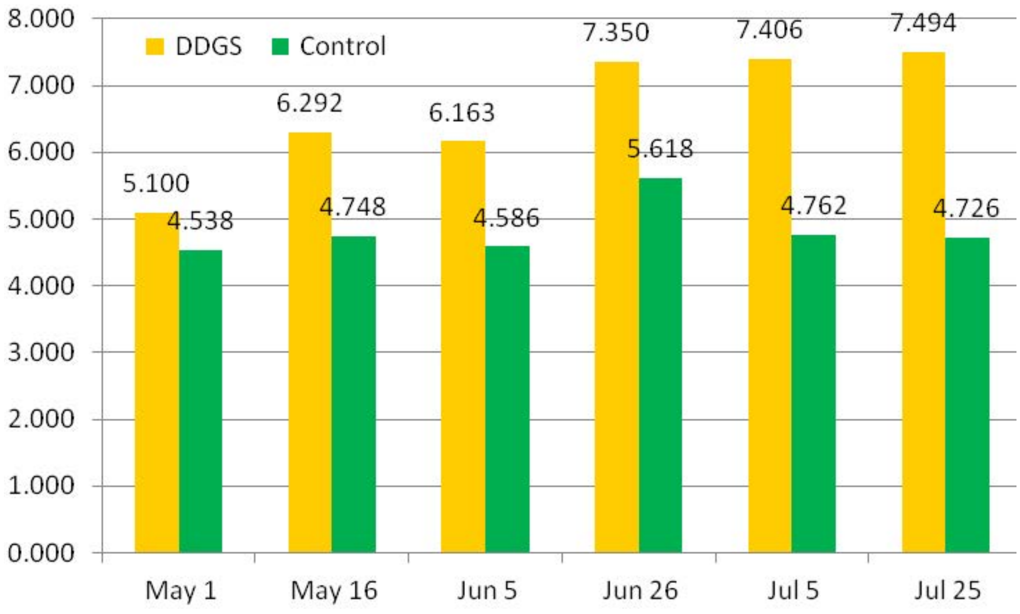


Figure 2. Average milk production (liters) for the entire feeding trial

Table 2. Comparison of commercial and DDGS supplement cost per cow per day

Supplement	Concentrate/cow per day, kg	$ Mx pesos/kg concentrate	pesos/cow/day
DDGS	2	$5.76	$11.52
Commercial	2	$5.00	$10.00
Difference	-	$0.76	$1.52

Table 3. Comparison of gross and net income from feeding the commercial and DDGS supplements per cow per day

Supplement	Milk/cow/day, liters	Mx pesos/liter	Gross income Mx pesos
DDGS	7.494	$5.20	$38.97
Commercial	4.726	$5.20	$24.58
Difference			$14.39

Recent Demonstration Trials in Vietnam

Dairy Cattle

Effect of feeding corn corn DDGS on milk
production under hot climate conditions in Vietnam

ABSTRACT

A feeding trial on US corn DDGS was conducted at commercial dairy farm during hot condition in Vietnam in 2010. One hundred and fifty six dairy cows in later stage of milk production were allotted randomly in three groups to contain 52 cows with similar milk production. Three dietary treatments comprised 1. Control diet, 2. Diet with 7.5 percent DDGS and 3. Diet with 15 percent DDGS. The diets were formulated to contain similar nutrient profile and comprised forages (corn, elephant grass and alfalfa hay), brewery waste, soybean curd waste, corn, soybean meal, molasses and commercial dairy supplement. The diet was manufactured locally in total mixed ration system and the diet was delivered two times per day. Milk production, feed consumption and milk quality was measured five days before the trial and 45 days after trial. Result demonstrated that feeding DDGS would support higher milk production without affecting feed consumption. Feeding DDGS at 7.5 percent and 15 percent resulted in higher milk production at 2 and 4 kg/day respectively compare to cows fed control diet. Feed intake remained unaffected at around 35 kg/day. Milk quality as measured by total solid and fat content was similar between cows fed control diet and DDGS at 7.5 percent. Feeding DDGS at 15 percent tend to have slightly better total solid and fat content. Feeding DDGS was able to reduce cost of the diets; diet cost for control, DDGS 7.5 percent and DDGS 15 percent were VND/kg 2537, 2460 and 2399, respectively.

INTRODUCTION

DDGS is a by-product of ethanol industry from fermentation of corn and has used for animal feeding. Increase of ethanol production in the U.S. for the last 10 years has resulted in a higher amount of DDGS becoming available for animal feed. It was estimated that 30 million tons of DDGS was produced in 2009 and 4.5 million tons was exported to different countries around the world.

Research on feeding DDGS for dairy has been conducted in many universities for the last 20 years. Based on 23 studies investigating the inclusion of DDGS in dairy cow diets with 96 treatment comparisons, Kalscheur (2005) conducted a meta analyses and reported that in general, DDGS is considered are considered to be highly palatable and stimulated feed intake when DDGS are included up to 20 percent of the dry matter in dairy cow diets. Milk production was not impacted by the form of DDGS fed, but there was a curvilinear response to increasing DDGS in dairy cow diets. Cows fed diets containing 4 to 30 percent DDGS produced the same amount of milk, approximately 0.4 kg/d more, than cows fed diets containing no DDGS. When cows were fed the highest inclusion rate (more than 30 percent) of DDGS, milk yield tended to decrease. It is recognized that DDGS quality has changed over this time period.

In the U.S., initially DDGS is fed in wet form without drying to the cattle raised in proximity to the ethanol plant. Increasing numbers of modern ethanol plant have resulted in more DDGS being produced in dried form. Feeding trials of DDGS conducted in the U.S. using DDGS derived from the older technology has darker color. Power et al. (1995) reported that feeding darker color of DDGS resulted in a lower milk production compared to DDGS in lighter color.

DDGS is a very good protein source for dairy cows. According to Schingoethe (2004), the protein content in high quality DDGS is typically more than 30 percent on a dry matter and DDGS contains 10 percent fat. DDGS is a good source of ruminally undegradable protein (RUP), or by-pass protein and the content was 55 percent. DDGS is also a very good energy source for dairy cattle with Total Digestible Nutrient (TDN) value 77 percent, NE_{gain} 1.41 Mkal/kg, and $NE_{lactation}$ 2.26 Mkal/kg. This new energy value of DDGS is reported 10 to 15 percent higher than that reported by NRC (2001).

Most of the DDGS research involving dairy cattle has been conducted in temperate climates. Chen and Shurson (2004) reported from field feeding trials of DDGS to dairy cows conducted during summer period in Taiwan that inclusion of DDGS 10 percent in total mix ration (TMR) was able to increase milk production at 0.9 kg/day without affecting feed intake. DDGS can also be fed to growing heifers, but the trial was limited; Kalscheur and Garcia (2004) reported that DDGS could be fed to heifers up to 40 percent in the rations.

The dairy industry in Vietnam is majority located in the south tropical areas and expanded to the central and north. The summer period in the north will be critical in feeding dairy as the feed consumption decreases significantly and DDGS can be valuable feed ingredient for dairy cattle. Vietnam has been importing DDGS from the U.S. from the last four years, but mainly used for swine and poultry feed and lately on fish feed. Currently no DDGS has been used for feeding dairy cattle despite 250.000 head of dairy cattle in Vietnam. Dairy production increased significantly in the last five years and it was predicted that dairy production will increase greater than 10 percent annually. Potential of DDGS for dairy cattle is significant, it was estimated that if 1 kg of DDGS can be fed to cattle every day, Vietnam may require 250.000 metric tons of DDGS per year. Vietnam has been importing DDGS from the U.S. from the last four years, but mainly used for swine and poultry feed.

Dairy cattle is normally fed green roughage and supplemented by a concentrate comprised industrial by products such as soybean meal, wheat bran, rice bran, cassava waste, cassava, molasses, and mineral/vitamin mix. However, the use of DDGS in Vietnam is not known and it would be useful information if a feeding trial of DDGS can be conducted specific to dairy cattle in Vietnam.

MATERIALS AND METHODS

Feeding trial was carried out at commercial dairy farm of PHU LAM, Tuyen Quang, Vietnam.

Feeding trial comprise three dietary treatments:

A. Control diet without DDGS in the form of total mixed ration

B. Diet contained 7.5 percent DDGS in the form of total mixed ration

C. Diet contained 15 percent DDGS in the form of total mixed ration

The feeding trial was conducted in randomized complete design using three groups of dairy cows in similar milk production and each group of cows was placed in pen to contained 52 dairy collected randomly from population of cows available in the farm. The cows were selected from the latest stage of milk production with average milking days greater than 200 days. Phu Lam Dairy Farm feedmIll in Tuyên Quang manufactured the dietary treatments according to formula met dairy requirement in TMR form. The feed was formulated similar in nutrient composition as presented in Table 1.

Each dietary treatment was fed to three groups of dairy cows placed in existing pen containing 52 cows per pen; therefore total 156 dairy cows were used. Each treatment was fed for 45 days and data on milk production from individual cow and feed consumption was collected five days prior to feeding and 45 days after feeding.

Feeding system

Feeding system was conducted according to the existing system at Phu Lam Dairy Farm Dairy farm. Total mixed ration comprised of roughage (Napier grass and corn forages) and mixed with other ingredients including cassava, soybean curd waste, brewery waste, ground corn, soybean meal, supplement from feedmIll (40 percent), molasses, solid fat and mineral-vitamin premixes. The least cost formulation was performed to provide sufficient nutrient to the cows need as suggested by NRC (2001). Cows were fed 2 times daily and feed refuse was weighed daily. Amount of feed was calculated based on the cows and milk production.

Measurement

Measurement was conducted for daily milk production, feed intake and milk quality comprises protein, fat, total solid and density. For milk quality, five samples was collected for each dietary treatment at mid and end of trial, therefore total 15x2 = 30 samples of milk was analyzed.

Statistical analyses

Data collected were analyzed for using Proc. GLM of SAS program and any significant different was further analyzed by Duncan test (SAS ver. 6.12).

RESULTS AND DISCUSSION

Environmental conditions

Average daily temperature and relative humidity of animal house during May to June 2010 when the feeding DDGS was performed is presented in Table 2. These months are well known as the hottest months of the year in northern part of Hanoi, Vietnam. The temperature reached maximum at 37°C or 99°F with humidity reached 88 percent. The animal house is open and supported by fan only.

Milk production and feed consumption

Average feed intake and milk production of cows before and after feeding different level of DDGS is presented in Table 3.

Milk production of cows before feeding DDGS is higher than cows after feeding DDGS as the trial was performed at later stage of milk production, therefore milk production decreased with continue feeding. The difference in milk production before and after feeding indicated the effect of dietary treatment on milk production. Table 3 shows that difference in milk production is more pronounce in cow fed control diet compare to cow fed DDGS. The cow fed diet containing 7.5 percent DDGS has the milk production difference 4.0 kg/day while the control treatment resulted in 6.1 kg/day difference. Higher feeding of DDGS at 15 percent in the diet resulted in the difference in milk production only 2.1 kg/day. Feeding DDGS significantly resulted in higher milk production compare to the control diet.

Daily milk production of cow fed different level of DDGS is presented in Figure 1. All cows' milk production is in declining stage as they were in later day milk production. Figure 1 indicated clearly that milk production from the control diet declined in much faster rate than cows fed DDGS 7.5 percent and the least decline was found in cows fed DDGS 15 percent in the total mixed ration.

Results of this trial shows clearly that feeding DDGS is able to maintain higher milk production during hot temperatures in Vietnam. Feeding DDGS at 15 percent in the total mixed ration was able to produce 4 kg more milk compare to cows fed control diets. This result was in agreement with

Table 1. Dietary formula of Total Mixed Ration containing DDGS at 0, 7.5 percent and 15 percent for feeding dairy cattle at Vinamilk, Tuyen Quang

Ingredients	Control	DDGS 7.5 percent	DDGS 15 percent
Corn silage	29.40	29.40	29.40
Elephant grass	28.01	29.40	29.40
Alfalfa hay 22	9.80	5.91	5.00
Brewery dried grains	7.35	7.35	7.35
Soybean curd waste	7.35	7.35	4.51
Corn, ground	6.00	1.80	
Molasses	4.90	4.10	4.90
Dairy concentrate 40% (guyomarch)	3.40	3.40	3.40
Soybean meal	2.75	2.75	
Solid fat (bergafat)	0.39	0.39	0.39
Di calcium phosphate	0.30	0.30	0.30
Sodium bicarbonate	0.30	0.30	0.30
Vitamin + mineral premixes	0.05	0.05	0.05
DDGS %		7.50	15.00
Calculated nutrient content based on dry matter			
Moisture %	51.7	52.8	53.0
Total digestible nutrient %	70.6	72.0	72.7
Net energy lactation (mcal/kg)	1.72	1.76	1.78
Crude protein %	15.1	17.1	17.0
Neutral detergent fifer %	29.8	33.3	38.6
Acid detergent fiber %	18.3	19.1	20.6
Calcium %	1.02	0.91	0.87
Phosphorus %	0.45	0.51	0.54
Sodium %	0.27	0.29	0.32
Magnesium %	0.21	0.20	0.20
Sulfur %	0.18	0.19	0.21
Udp %	8.6	9.7	9.3
Rup %	6.8	7.4	7.8
Cost (VND/kg)	2537	2460	2399

Table 2. Temperature and relative humidity of animal house during feeding trial on DDGS

	Temperature (^{o}C)	Relative Humidity (%)
Minimum	28	74
Maximum	37	88
Average	33	82

the feeding DDGS during summer period in Taiwan that feeding DDGS at 10 percent in the diet was able to increase milk production at 1 kg/day (Chen and Shurson, 2004). The current trial in Vietnam showed a better production yield compare to the trial conducted in Taiwan.

Table 3 shows that average daily feed consumption is not affected by dietary treatment. Daily feed consumption of cows fed control diet is 35.6 kg while cows fed 7.5 percent and 15 percent DDGS is 35.3 and 35.6 kg respectively. There is also no difference in feed consumption of cows before feeding trial was started. DDGS diet was readily consumed by cows within few days of adaptation. Feeding DDGS was able to reduce cost of feed, Table 1 indicates that diet cost for control, DDGS 7.5 percent and DDGS 15 percent were VND/kg 2537, 2460 and 2399, respectively. It is calculated that every inclusion of 10 percent DDGS in the dairy cows diet, the cost of feed will decrease VND 95/kg or around four percent.

Fluctuation in daily feed intake was noticed during feeding trial and the data is presented in Figure 2. It was noticed that there is no difference in feed consumption between dietary treatments. The feed intake fluctuation was related with the temperature and humidity of the house during the day. When the temperature increased and humidity was high, the cows tended to reduce feed intake while feed consumption was higher at lower temperature.

Milk quality

Milk quality was measured based on total solid and fat content and the result of measurement of milk quality before and after feeding DDGS is presented in Table 4. Total solid and fat content of milk from cow fed 7.5 percent DDGS was not different with that milk from cows fed control diet. There is slightly higher total solid and fat content when cows fed 15 percent DDGS in the ration. These results indicate that feeding 15 percent DDGS improved milk quality compared with milk quality before DDGS was fed.

Table 3. Average milk production and feed consumption of cows before (5 days) and after (45 days) feeding DDGS at different level under hot climate condition

Treatment	Milk Production (kg/day)		Difference (kg/day)	Feed Consumption (kg/day)	
	Before DDGS	After DDGS		Before DDGS	After DDGS
Control	20.5	14.4^{a*}	6.1	36.8	35.6
DDGS 7.5%	19.2	15.2^{ab}	4.0	38.3	35.3
DDGS 15%	18.2	16.1^{b}	2.1	36.8	35.6

* Different superscript in the same column indicate significant different (P less than 0.05) and at Standard Error Means (SEM) 0.4 kg/day

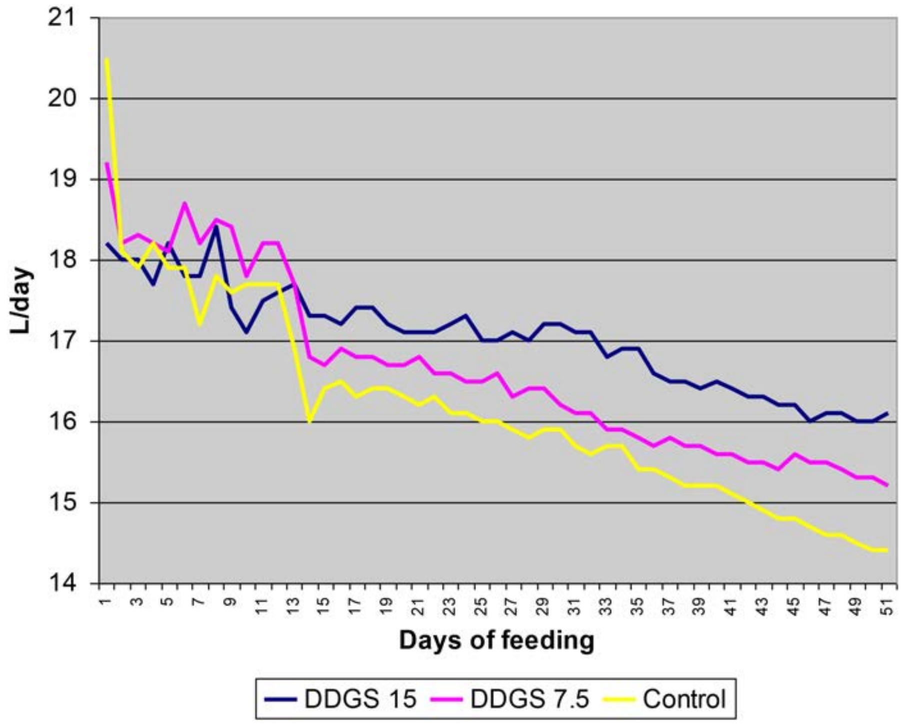


Figure 1. Daily milk production of cows fed different level of DDGS under hot condition in Vietnam

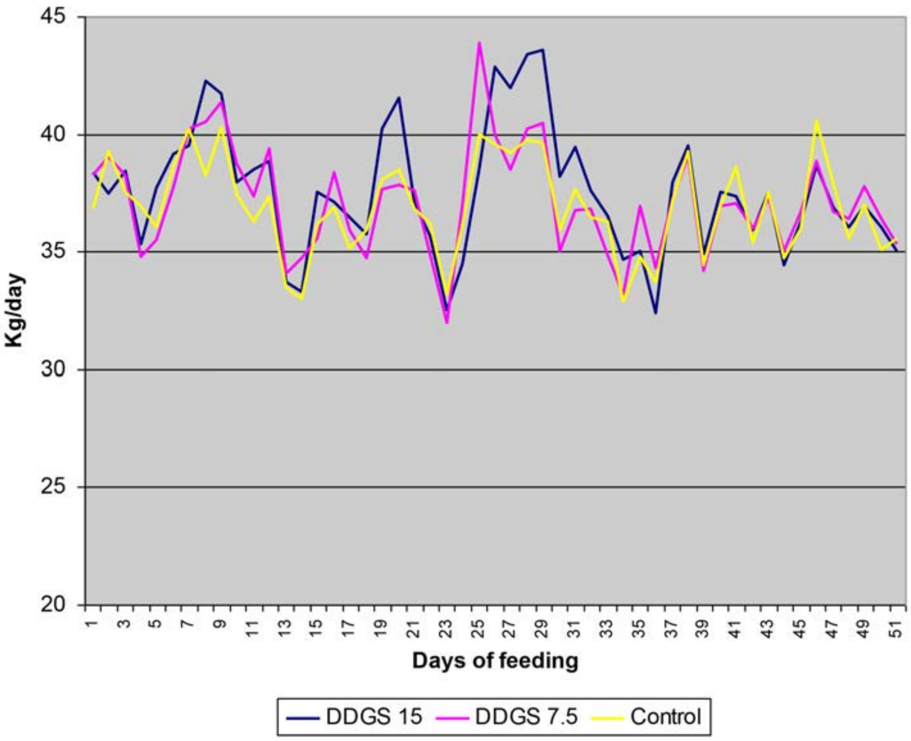


Figure 2. Daily feed consumption (kg/day) of cows fed different level of DDGS under hot condition in Vietnam

Table 4. Total solid and fat content of milk from dairy cow before and after feeding DDGS at different level under hot climate condition

Treatment	Total Solid (%)		Difference (%)	Fat Content (%)		Difference (%)
	Before feed	After feed		Before feed	After feed	
Control	12.5	12.1	-0.4	3.8	3.7	-0.1
DDGS 7.5%	12.4	12.1	-0.3	3.8	3.7	-0.1
DDGS 15%	12.0	12.4	0.4	3.6	4.0	0.4

CONCLUSIONS

1. Diets containing DDGS is readily consumed by dairy cows.
2. Feeding DDGS was able to improve milk yield of cow raised under hot climate condition.
3. Diet containing 15 percent DDGS was able to maintain the production and resulted in 4 kg higher compare to control diet, while diet containing 7.5 percent DDGS resulted in 2 kg higher.
4. Milk quality from cow fed 15 percent DDGS was tend to be better compare to that cow fed 7.5 percent and control diet.

ACKNOWLEDGEMENT

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Aquaculture

Effect of feeding DDGS to growth performance and fillet color of Pangasius

ABSTRACT

A feeding trial on corn DDGS was conducted to Pangasius catfish at the research farm of a private company in Vietnam in 2015. DDGS was obtained from the U.S. and was analyzed for chemical composition and amino acids content. Six thousand Pangasius fingerling at 40 g body weight were allotted randomly in 16 floating cages made of nylon net placed in 0.5 hectare pond at 3 m deep. The cages were divided into four groups of dietary treatments and replicated four times. Four dietary treatments were used DDGS 0 percent, DDGS 5 percent, DDGS 10 percent and DDGS 15 percent containing 0, 50, 100 and 150 g g/kg of DDGS in the diets respectively. The diets were formulated to have same nutrient content using soybean meal, rice bran, cassava, fish meal, wheat and wheat bran. The fish was fed starter diet and continued with grower diets containing 280 g g/kg and 260 g g/kg respectively in floating form. The feeing trial was performed for 118 days but fish sampling was conducted after feeding 42 and 78 days. The diets containing DDGS were consumed readily by Pangasius. The results showed that there is no different on growth performance of Pangasius fed different levels of DDGS. Body weight of the fish fed DDGS 0 percent, 5 percent, 10 percent, 15 percent were 471, 472, 470 and 490 g, respectively, while gain:feed ratio were 1.59, 1.62, 1.56 and 1.53 respectively. There was no different in fish mortality due to dietary treatments. Fillet yield was improved slightly by feeding DDGS, from 526 g g/kg in Pangasius fed no DDGS to 531 g g/kg fed 150 g g/kg DDGS. Fish fillet color measurement by color different meter showed that L, a and b values were not statistically different due to dietary treatments and prolonged feeding of DDGS up to six months did not show color values differences related with yellowness. In conclusion, corn DDGS can be successfully fed to Pangasius and feeding DDGS up to 150 g g/kg in the diet did not affect the fillet color.

INTRODUCTION

DDGS (Distiller Dried Grains with solubles) is a by-product of the ethanol industry and contains a mixture of distiller grains with solubles from fermentation of corn and it has used for animal feeding. Increase of ethanol production in U.S. for the last 15 years has resulted in a higher amount of DDGS become available for animal feed. It was estimated that greater than 40 million tonof DDGS is produced in 2014 and greater than 10 million tonis exported to different countries around the world (USGC, 2014). It has been shown to be economically feasible for animal feed especially in dairy cattle, swine and poultry.

Catfish is one of major fish grown in Vietnam and is considered popular species for human consumption locally. Catfish from Vietnam has been exported to many different countries in Europe, the U.S. and the Asia Pacific region. It is grown in a pond water or cage system in river areas in Mekong Delta Vietnam. Catfish is cultured until market size in the range of 500- 1000 g. Catfish feed is commonly made of several ingredients such as soybean meal, wheat by products, fish meal, rice by product, cassava etc.

Limited data was available on feeding value of DDGS as Pangasius catfish feed. DDGS has been fed successfully to channel catfish; Tidwell et al. (1990) conducted an experiment over an 11-week period where channel catfish fingerlings were fed diets containing 0 percent, 10 percent, 20 percent and 40 percent DDGS, replacing some of the corn and soybean meal. In 1993, Webster et al. conducted feeding study to juvenile catfish and suggested that up to 30 percent DDGS can be added to channel catfish diets with no negative effects on growth performance, carcass composition or flavor qualities of the filets. Therefore, DDGS is considered an acceptable ingredient in diets for channel catfish (Tidwell et al., 1990; Webster et al., 1991).

However the early DDGS trials were performed using DDGS manufactured by old technology, while ethanol production technologies have evolved to modern or new technologies by using advance fermentation including the use of selected enzymes, yeast and modern processes. Currently in the U.S. there are more than 200 ethanol plants established in the last 20 years and DDGS has a better quality and brighter yellow color. Earlier data indicated that new DDGS can be fed successfully to replace plant protein sources for tilapia (Coyle et al., 2004; Shelby et al., 2008) and channel catfish (Robinson and Li, 2008, Li et al., 2010, 2011, Zhou et al., 2010). Cheng and Hardy (2004) was able to use DDGS up to 15 percent in the diet of trout to replace fish meal and recent study by Overland et al., 2013 reported that DDGS could be included in rainbow trout diet up to 10 percent to replace other plant protein sources including sunflower meal, rapeseed meal and field peas.

Most of aquaculture production especially fresh water fishes are located in Asia and Vietnam is a leading country to produce catfish for local consumption and export. Vietnam catfish are slightly different from U.S. channel catfish, Vietnam catfish was originated from Mekong River and named Pangasius hyphotalamus. Vietnam catfish production continues to increase in the last few years and fillet of Pangasius has been exported to many different countries. However, many exporters demanding the fillet to be white in color as requested by consumers. There is a concern that feeding corn DDGS may result to the different color of fillet as the color substances from DDGS might be transferred to the fillet. This assumption has never been proved from the research except Webster et al., 1993 reported that feeding

DDGS did not affect fillet flavor quality. Therefore the purpose of the trial was to evaluate feeding value of DDGS and its effect to fillet color of Pangasius.

MATERIALS AND METHODS

A trial on growth performance was carried out at experimental farm of Hung Vuong Co., Mekong Delta Sadec, Vietnam while feed production for the trial was performed at Hung Vuong feedmIll. Fish culture was performed in 16 floating cages at size 4x6x3m placed in a pond at size $5000m^2$ with 3 m deep. Fresh water for the pond was obtained from Mekong River. Cages were placed in such way that provides sufficient water movement and exchange. Daily water quality measurement was performed and indicated that pH of water is stable at 8 and dissolved oxygen is 4, while daily temperature ranged from 28 to 32 °C.

Diets

Feeding trial used four dietary treatments comprise 1) Control diet without DDGS (DDGS 0 percent), 2) Test diet containing 50 g kg^{-1} DDGS (DDGS 5 percent), 3) Test diet containing 100 g kg^{-1} DDGS (DDGS 10 percent) and 4) Test diet containing 150 g kg^{-1} DDGS (DDGS 15 percent). Two types of diet were formulated for starter and grower which contain 28 percent and 26 percent protein respectively following common practice of Vietnam industries. The experimental diets were formulated to contain same nutrient content and presented in Table 1.

The size of pellet for starter feed would be 3-4 mm while for grower feed at 5-6 mm. Each dietary treatment was fed to Pangasius fish at size 40 g. The fish was grown in floating cage made of nylon net (mesh 1) at size 4x6x3 m (effective volume for water 72 m3) containing 300 fish per cage. Each treatment was replicated four times and the trial was performed for 118 days to reach marketable size which approximately 500 g. It was decided that after growth trial was completed, 50 fishes were kept in smaller cages and continued feeding the diets up to six months for fillet color measurement.

Table 1. Diet composition of Catfish feed containing different level of DDGS

	Starter Diet (280 g g/^{kg} protein)				Grower Diet (260 g g/^{kg} protein)			
Ingredients	DDGS 0%	DDGS 5%	DDGS 10%	DDGS 15%	DDGS 0%	DDGS 5%	DDGS 10%	DDGS 15%
Soybeanmeal,Arg.[1]	487.0	468.2	456.2	428.2	447.0	428.0	424.0	412.0
Rice bran, full fat	224.5	145.1	154.6	133.6	233.0	202.0	166.0	125.0
Wheat bran	0.0	0.0	0.0	0.0	50.0	50.0	50.0	15.0
Defatted rice bran	50.0	100.1	50.0	0.0	0.0	0.0	0.0	0.0
Cassava	120.0	120.1	120.1	165.1	120.0	120.0	120.0	120.0
Wheat	50.0	50.0	50.0	50.0	80.0	80.0	80.0	117.5
Fish meal, 62	40.0	40.0	40.0	47.5	30.0	30.0	30.0	30.0
Fish meal, 55	12.0	12.0	14.5	11.0	26.0	26.0	16.0	15.0
DDGS	0.0	50.0	100.0	150.0	0.0	50.0	100.0	150.0
Premix[2]	10.5	10.5	10.5	10.5	8.0	8.0	8.0	8.0
Salt	6.0	4.0	4.0	4.0	6.0	6.0	6.0	6.0
Mono Calcium Phosphate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5
Total	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000

1:Arg.=Argentina,2:PremixcontainVitaminandTraceElementprovidedperkgofdiet:iron,50mg;copper,30mg;manganese,20mg;zinc,30mg;cobalt,0.1mg;selenium,0.1mg. vitaminA(retinylacetate),7,000IU;vitaminD3(cholecalciferol),1,000IU;vitaminE(DL-α-tocopherylacetate),50IU;vitaminKactivity,3mg;thiamine,6mg;riboflavin,7mg;pantothenic acid, 15 mg; niacin, 40 mg; pyridoxine, 6 mg; folic acid, 2 mg; biotin, 0.1 mg

Feeding system

At least 6,000 fingerling of Catfish Basa at size 40 g (16 cages x 300 fish= 4800) was purchased from supplier and was adapted in the cages before the trial is started. Initially feed was offered at 5 percent biomass and fed four times per day at 7:30 am, 10:30 am, 13:30 pm and 15:00 pm. Amount of feed given was based on 95 percent satiation. Initial of feed was given at amount that can be consumed by fish within 10 minutes multiplied by 90 percent and was given in that amount for five days. The following five days was given at full amount therefore the average would be 95 percent satiation. This calculation was repeated again for every 10 day period.

Sampling and measurement of performance

Fish sampling was performed from every cage by collecting fish using a bucket after 42 and 78 days of feeding while total weighing was performed when they reached approximately 500 g at 118 days of feeding. The daily mortality and feed consumption was recorded. At end of feeding period (118 days), total fish were weighed from each cage and residual feed was measured. Feed conversion ratio was calculated and corrected for the mortality weight. DDGS samples were analyzed for proximate composition at Hung Vuong laboratory. Moisture, protein, crude fiber, ether extract and ash were analyzed according to Method EC 152/2009, TCVN 4328-1:2007, AOCS Ba-6a-05, ISO 6492:1999 and EC 152/2009, respectively.

Experimental grower diets were analyzed for AA contents at Evonik SEA Laboratory in Singapore. Samples (diets) for amino acid analyses were hydrolyzed in 6 N HCl for 24 h at 110 ˚C under nitrogen atmosphere. Performic acid oxidation was carried out before acid hydrolysis for methionine and cysteine analysis (AOAC International, 2000; 982.30 E [a, b, c]). The amino acid in the hydrolysate was subsequently determined by high performance liquid chromatography after postcolumn derivatization. Amino acid concentrations were not corrected for incomplete recovery resulting from hydrolysis.

Fillet color measurement

At end of feeding trial at 118 days, five fish samples were collected from each cage randomly, therefore total 20 fishes were collected from each treatment and the fillet was collected manually and weighed. Fillet yield was measured as percentage from total weight of fillet divided by weight of fish The fillet color measurement was performed using portable Nippon Denshoku NR-3000 color difference meter and expressed on L, a and b as Hunter Lab system. L value may indicate lightness and b indicates yellowness, while a value indicates redness. After growth trial was completed, it was decided to continue feeding DDGS to Pangasius until the size of fish reached around 0.9-1.0 kg and after 184 days, the fish sampling and color measurement of fillet was performed in similar method.

Statistical analyses

A randomized complete design with four treatments and four replicates containing 300 fishes per replicate cage was used in this trial for each species of fish. Data was analyzed using computer program (SAS ver. 6.12) and any significant different due to the treatment was further analyzed using Duncan.

RESULTS

DDGS and diet composition

Composition of corn DDGS used in this experiment is presented in Table 2. Protein content is 277.3 g g/kg while fat content is 98.8 g g/kg which indicate that this is a regular DDGS found in the U.S. with high oil content. Protein content estimated by near infrared spectroscopy is 276.5 g g/kg shows a similar result with protein content estimated by wet chemical method. Amino acids content in this DDGS is also a typical for U.S. corn DDGS with lysine level around 8 g g/kg and methionine 5 g g/kg.

Two types of feed were formulated to contain similar nutrient content when DDGS was included at 0, 50, 100 and 150 g g/kg. The composition of test diets for starter feed and grower feed is presented in Table 3. All starter or grower feed contains similar composition as expected. The starter feed contains 288-296 g g/kg protein and they are slightly higher than expected in formulation at 280 g g/kg. Similarly for grower feed, the analyzed protein content are 274-284 g g/kg, a slightly higher than expected in formulation at 260 g g/kg. Analyzed starch levels in all diets are around 300 g g/kg and this level is maintaining the same in all dietary treatments. High level of starch was formulated to produce floating feed.

The amino acids composition of grower feeds is presented in Table 4. There is a little variation in amino acids content among dietary treatments. Lysine content is maintained at around 16 g g/kg while methionine at 5.9 g g/kg. Those amino acids content is presented as total amino acids derived from feed ingredients and supplement. Analysis result indicated that all diet received only supplemental methionine at level 1.5-1.6 g g/kg feed. Total amino acids in all dietary treatments are 271-279 g g/kg and this figure would be similar to the result of protein content reported earlier.

Growth performance

Body weight of Pangasius fed different level of DDGS is presented in Figure 1. Pangasius grew well by feeding DDGS, body weight reached 150 g, 300 g and 470 g after feeding for 42, 78 and 118 days respectively. There is no statistical different in body weight among the dietary treatments at end of trial, however there is statistical difference due to treatment after feeding for 42 days. Feeding DDGS gave slightly higher body weight compare to control diet without DDGS. However the effect of DDGS disappeared after longer feeding at 78 and 118 days.

Performance of Pangasius after feeding different level of DDGS for 119 days is presented in Table 5. There is no statistical different on body weight of Pangasius after feeding different level of DDGS, although the highest body weight of Pangasius is found in fish fed highest level of DDGS (490 g) compare to control diet without DDGS at 471 g. There was no statistical different in feed consumption, which indicated that inclusion DDGS up to 15 percent did not affect palatability of Pangasius to consume feed. gain:feed ratio is also not affected by the dietary treatment but the lowest gain:feed ratio is found in fish fed 15 percent DDGS (1.53) compare the fish fed no DDGS or 50 g g/kg DDGS at 1.59 and 1.62 respectively. Mortality of fish was also not different among dietary treatment and the average mortality is between 3.7-4.9 percent.

Table 2. Composition of DDGS and essential amino acids level used in the trial

Analyzed Composition	Amount g g/^{kg}
Moisture	114.1
Crude protein	277.3
Crude fiber	76.9
Fat	98.8
Ash	45.0
Amino acids (Essential)	
Protein (NIRS)	276.5
Threonine %	10.02
Cystine %	5.02
Valine %	13.03
Methionine %	5.08
Isoleucine %	9.58
Leucine %	29.90
Phenylalanine %	12.74
Lysine %	7.91
Histidine %	7.28
Arginine %	11.79
Trytophan %	2.21

Table 3. Analyzed composition and starch level of diets containing different level DDGS (g g/^{kg})

Diet	Moisture	Protein	Fat	Fiber	Ash	Calcium	Phosphorus	Starch
Starter Feed, 280 g g/^{kg} Protein								
DDGS 0%	103.6	290.2	56.2	35.2	88.0	14.0	13.1	301.2
DDGS 5%	88.6	287.7	52.6	40.3	88.9	13.8	10.5	311.4
DDGS 10%	88.7	296.3	51.3	39.1	85.4	13.4	11.5	310.5
DDGS 15%	84.5	292.8	52.6	40.0	83.8	14.0	11.3	317.6
Grower Feed, 260 g g/^{kg} protein								
DDGS 0%	99.7	273.6	63.6	38.7	91.5	13.5	10.8	308.6
DDGS 5%	95.1	277.1	59.4	38.8	86.3	13.2	11.3	303.9
DDGS 10%	97.0	277.6	55.2	39.0	86.5	14.1	11.6	308.7
DDGS 15%	98.5	284.2	49.0	37.5	84.0	13.6	11.8	320.3

Table 4. Amino acids composition of grower diets containing different level of DDGS (g 100g^{-1})

Amino acids	DDGS 0%	DDGS 5%	DDGS 10%	DDGS 15%
Methionine	0.59	0.57	0.59	0.60
Cystine	0.42	0.42	0.44	0.43
Methionine + Cystine	1.01	0.99	1.03	1.03
Lysine	1.67	1.62	1.63	1.58
Threonine	1.13	1.11	1.14	1.13
Tryptophan	0.37	0.37	0.37	0.36
Arginine	2.07	2.03	2.05	2.00
Isoleucine	1.25	1.24	1.27	1.26
Leucine	2.12	2.15	2.29	2.32
Valine	1.39	1.38	1.42	1.41
Histidine	0.71	0.71	0.74	0.73
Phenylalanine	1.37	1.37	1.42	1.41
Glycine	1.43	1.43	1.46	1.46
Serine	1.41	1.40	1.45	1.43
Proline	1.54	1.60	1.70	1.72
Alanine	1.37	1.40	1.48	1.50
Aspartic acid	3.02	2.96	3.00	2.93
Glutamic acid	4.74	4.72	4.89	4.84
Total (without NH 3)	26.60	26.47	27.31	27.09
Ammonia	0.59	0.59	0.61	0.63
Total	27.18	27.06	27.93	27.72

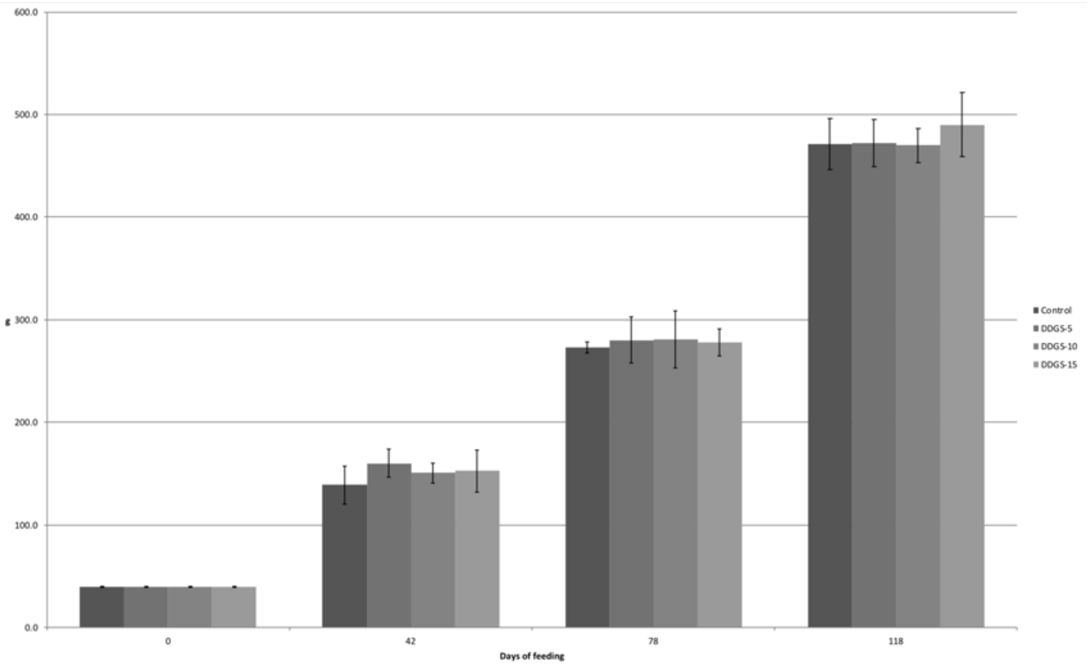

Figure 1. Body weight of Pangasius after feeding diet containing DDGS at different level

Table 5. Performance of Pangasius after feeding different levels of DDGS for 119 days

Measurement	DDGS 0%	DDGS 5%	DDGS 10%	DDGS 15%	SEM**
No of fish/cage	300	300	300	300	
Weight at start (g)	39.8	39.8	39.8	39.9	0.17
Weight at harvest (g)	471.3	472.0	470.0	490.2	24.6
Weight gain (g)	431.5	432.2	430.1	450.3	24.6
Feed consumption (g)	698.2	708.7	674.4	691.5	48.0
Mortality %	3.7	4.9	4.0	3.7	2.0
Gain:Feed	1.62	1.65	1.57	1.54	0.064
Gain:Feed corr*	1.59	1.62	1.56	1.53	0.055

*corr= corrected with mortality, ** SEM=Standard Error Means

Fillet color

Results on fillet color measurement of Pangasius after feeding different level of DDGS for 119 days and 184 days is presented in Table 6 and 7 respectively while pictures of fillet is presented in Figure 2. Statistical analysis indicated that there was no significant different on color measurement of fillet after feeding 119 days. L, a and b value measured at anterior, middle and posterior position of fillet is not statistically different among dietary treatment. However there is difference in a value of fillet after feeding 184 days at anterior and posterior position but a value reflected redness in color while yellow color is reflected by b value and whiteness by L value. Yellow color of DDGS is originated from xanthophyll found in yellow corn and concentrated in DDGS during ethanol production. It seems that xanthophyll of DDGS is causing yellow color of fillet when DDGS is included up to 15 percent in the diet. Feeding DDGS for four months (119 days) did not affect fillet color and extended feeding up to six months also did not affect fillet color.

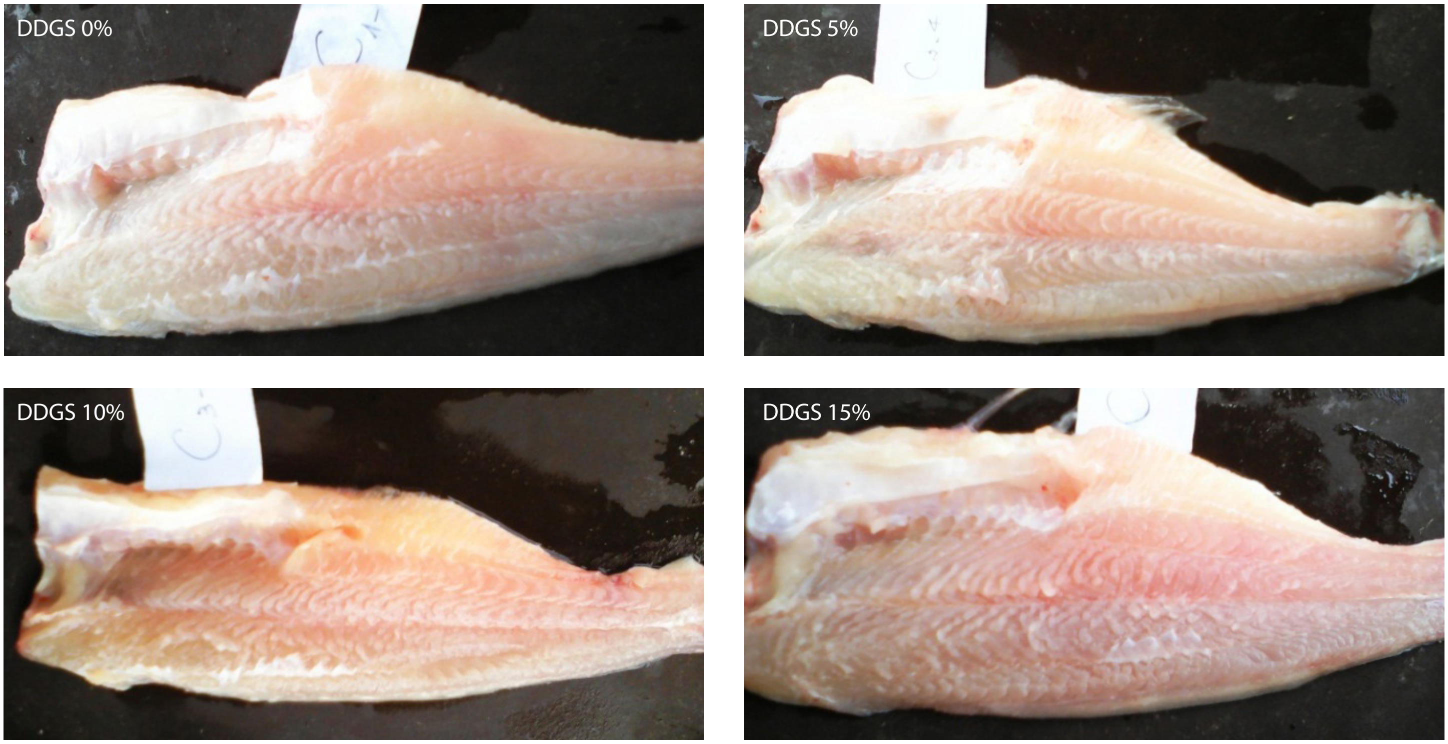

Figure 2. Fillet of Pangasius after feeding with different levels of DDGS for 118 days

Results on fillet yield measurement is presented in Table 6 and fillet color measurements are shown in Table 7. Fillet yield was slightly improved by feeding the DDGS diets compared to the control diet, with no general effects on fillet color.

DISCUSSION

With increasing availability of DDGS due to ethanol production, DDGS can be potentially used for fish feeding. DDGS contains 277 g g/kg protein and fat 99 g g/kg can be used as source of a feed for fresh water fish. In this experiment, DDGS can be used to replace rice bran and partly soybean meal. In previous feeding trial to channel catfish, DDGS was used successfully to replace corn and soybean meal (Tidwell, et al., 1990, Zhou et al., 2010) and in combination with cottonseed meal, DDGS can replace soybean meal (Robinson and Li, 2008) as far as the diet was supplemented with lysine. In this experiment, when DDGS was used up to 150 g g/kg in Pangasius diet, the diet should be supplemented with DL methionine (1.4 g g/kg) but not lysine. It is possible that in the current experiment, the inclusion rate of soybean meal in the diets were very high (greater than 400 g g/kg) and soybean meal is well known to contain high amount of lysine (around 30.8 g g/kg) but soybean meal is deficient in methionine (6.8 g g/kg) (NRC, 1993). Corn DDGS contains much lower lysine (7.9 g g/kg) compare to soybean meal and lysine in DDGS may be less digested for monogastric animals (Waldroup et al. 2007; Stein and Shurson, 2009). Therefore it is critical to formulate diet for fish carefully to consider amino acids composition and digestibility. Unfortunately digestible amino acids of DDGS for fish is not known, therefore digestibility coefficient of DDGS for poultry may be adopted. In the current experiment, the dietary treatments had been formulated to contain similar profile of amino acids as it is supported by the analysis result of amino acids content in the diets. DDGS however contains slightly higher crude fiber (76.9 g g/kg) compare to dehulled soybean meal (less than 35 g g/kg). High fiber may limit the utilization by fish but it depends upon inclusion rate and fish species. Recent report showed that DDGS inclusion rate should be limited to 100-200 g g/kg for rainbow trout (Welker et al., 2014) but can be tolerated up to 820 g g/kg in tilapia low protein diet if supplemented with synthetic lysine and tryptophan (USGC, 2012).

The diets containing DDGS up to 150 g g/kg in feed is readily consumed by Pangasius which may indicate that there is no palatability issue when DDGS is used in diets. The dietary treatments have been formulated to contain the same amount of starch (300 g g/kg) and all the feeds were able to float and there was no issue in manufacturing process. DDGS contain little starch as most of starch in corn

Table 6. Fillet yield and color of Pangasius fed different level of DDGS for 118 days

Treatment	Fillet (g g/kg)*	L anterior	a anterior	b anterior	L middle	a middle	b middle	L posterior	a posterior	b posterior
DDGS 0%	525.6^{a}	46.48	-4.95	7.52	48.59	-5.52	6.04	47.97	-3.37	7.27
DDGS 5%	539.1^{b}	47.23	-4.04	7.93	47.23	-5.14	7.74	48.58	-3.19	7.82
DDGS 10%	535.6^{b}	46.81	-4.54	8.03	47.96	-3.50	7.53	47.83	-4.00	7.74
DDGS 15%	530.9^{ab}	46.67	-4.76	7.83	48.59	-4.56	7.67	48.90	-3.93	8.56
P Value	0.030	0.595	0.755	0.851	0.463	0.332	0.268	0.449	0.685	0.268

*Different superscript in the same column indicate significant different (P less than 0.05)

Table 7. Fillet color of Pangasius fed different level of DDGS for 184 days

Treatment	L anterior	a anterior	b anterior	L middle	a middle	b middle	L posterior	a posterior	b posterior
DDGS 0%	46.50	-4.44b	-0.84	46.28	-2.23	-1.59	46.94	-1.24a	-1.21
DDGS 5%	46.61	-3.20ab	-0.45	45.73	-1.82	-0.27	47.08	-2.19ab	-0.30
DDGS 10%	46.61	-2.23a	-0.20	47.45	-3.10	-1.23	47.03	-3.53b	-0.21
DDGS 15%	47.52	-4.86b	-0.41	46.40	-2.74	-0.58	46.58	-1.18a	-0.08
P Value	0.288	0.040	0.804	0.089	0.439	0.145	0.950	0.024	0.392

*Different superscript in the same column indicate significant different (P less than 0.05) is converted to become ethanol and carbon dioxide during fermentation process. Therefore feed containing DDGS up to 150 g g/kg should be able to be manufactured for floating feed when starch level is considered.

Pangasius was able to grow well when DDGS was included up to 150 g g/kg in the diet. In the initial stage during growing (42 days), inclusion of DDGS in the diet was able to give better growth rate but the effect disappear on later stage of growing. Inclusion of DDGS may provide positive effect to tilapia, Wu et al. (1994) reported that diets containing either corn gluten meal (180 g g/kg) or DDGS (290 g g/kg) and 320 g g/kg or 360 g g/kg crude protein, resulted in higher weight gains for tilapia than fish fed a commercial fish feed containing 360 g g/kg crude protein and fish meal for tilapia with initial weight of 30 g. In a subsequent study, Wu et al., (1996) evaluated the growth responses over an eight week feeding period of smaller tilapia (0.4 g initial weight and concluded that feeding diets containing 320 g g/kg, 360 g g/kg and 400 g g/kg protein and 160- 490 g g/kg protein-rich ethanol co-products will result in good weight gain, feed conversion and protein efficiency ratio for tilapia fry. Previous study of feeding DDGS to tilapia in Vietnam indicated an improvement on survival rate when DDGS was included in the diet up to 150 g g/kg (Tangendjaja and Chien, 2007).

At the end of the feeding trial on DDGS, performance of Pangasius is not different among dietary treatments, inclusion of DDGS at 50, 100 and 150 g g/kg diet did not affect body weight gain, feed consumption and gain:feed ratio. Mortality was also not affected by feeding DDGS. The improvement on mortality found in tilapia trial was not noticed in this Pangasius trial. It is not known if there is species difference in mortality because of feeding DDGS. Lim et al., (2009) reported possible resistance of fish to Edwardsiella ictaluri challenge when the diets contain DDGS. However recent study by Overland et al., 2013 showed that feeding DDGS did not affect blood parameter of trout. DDGS contain residual yeast (Sacharomyces cerevisiae) from fermentation (Ingledew, 1999) and yeast cells especially cell wall has been reported by Li and Gatlin III, 2006 and Refstie et al., 2010 as sources of mannan oligosaccharides and β-glucans that can be used as immunostimulants in fish diets and finally influence fish health and reduce morality.

DDGS contains reasonable amount of xanthophyll if it is derived from yellow corn. The xanthophyll content may reach up to 59 mg g/kg and xanthophyll in DDGS has been shown that it can be transferred to yolk and improve the yolk color (Tangendjaja and Wina, 2011). Yellow color of yolk can be desirable for consumers, however yellow color may not be desirable for fish fillet consumers. Many Pangasius industries in Vietnam demanded that the fillet should have white in color and yellow color may not be desirable. In the present study, fillet color of Pangasius is not affected by feeding DDGS up to 150 g g/kg in the diet for 118 days and prolong feeding of DDGS until six months so the fish reached around 900 g size did not affect fillet color. It is important to note that Vietnam industries would normally harvest Pangasius to produce fillet for export when fish reach body weight around 1 kg. Previous study (Tangendjaja et al. 2012,unpublished) indicated that xanthophylls content of fillet of catfish fed 150 g g/kg DDGS is 1.1 ppm and no different in control diet without DDGS at 2.0 ppm, while xanthophylls content in DDGS is 30 ppm. This indicates that feeding DDGS 150 g g/kg did not increase xanthophylls content of the fillet of catfish and this result supports the result of color measurements of fillet in Table 6 and 7. The different results between coloring ability of DDGS for yolk and fillet may be associated with the different of tissue. Carotenoids including xanthophylls are compound that are soluble in fat and fat in egg is located in yolk rather than white albumen. In contrast to Pangasius fillet, that largely protein tissue, xanthophyll may not be deposited in the fillet and resulted that yellow color was not detected in Pangasius fillet after feeding DDGS up to 150 g g/kg in the diets.

CONCLUSIONS

Results from this study demonstrated that corn DDGS can be valuable for feeding Pangasius as source of protein and energy to replace rice bran and partly soybean meal. Feeding DDGS up to 150 g g/kg in the diet of Pangasius did not affect growth performance (body weight gain, feed consumption and gain:feed ratio) and mortality. Fillet color of Pangasius measured by color different meter was not affected by feeding DDGS for six months.

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CHAPTER 30

Frequently Asked Questions about DDGS

Why are U.S. ethanol plants partially extracting oil before manufacturing DDGS?

The current market price and demand for crude corn oil is very economically attractive for U.S. ethanol plants to create another revenue source. The growth of the U.S. biodiesel industry has resulted in increased demand for fats and oils, and distillers corn oil is an economically attractive lipid source. The capital investment to add corn oil extraction equipment to existing ethanol plants is relatively low, and this investment can easily be fully recovered in less than one year (see Chapter 3).

Can distillers corn oil be exported for use in animal feed?

Yes. Distillers corn oil has an approved definition and quality specifications from the Association of American Feed Control Officials and significant quantities are being used in the U.S. poultry and swine industries. It is approved for use in biodiesel production and for animal feed, but not for human consumption. Recent studies have determined the metabolized energy and AME_n content of distillers corn oil for poultry and swine (see Chapter 4), and have shown that it is an economical and high energy lipid source for animal feed. Some U.S. marketers have experience in exporting distillers corn oil, and although large quantities are available, limited quantities have been sold.

Does reduced-oil DDGS have less energy than conventional high-oil DDGS?

Several studies have shown that the crude fat content of DDGS is a poor single predictor of metabolized energy content for swine and AME_n content for poultry (see Chapter 6). Prediction equations have been developed and validated using several chemical analysis measures to accurately predict metabolized energy and AME_n among DDGS sources with variable content for swine and poultry, respectively. In these equations, a measure of fiber is more predictive than crude fat content. Limited studies have been conducted to determine the net energy content of reduced-oil DDGS for dairy and beef cattle, but it appears to be slightly reduced in reduced-oil DDGS compared to high-oil DDGS. See Chapters 17 and 19 for more details on the net energy estimates of reduced-oil DDGS for ruminants.

How does partial extraction of corn oil in DDGS affect its feeding value?

Partial extraction of corn oil does not necessarily reduce the metabolized energy and AME_n content for swine and poultry because several studies have shown that some sources of reduced-oil DDGS have equal or greater metabolized energy and AME_n content than traditional high-oil DDGS sources. However, limited data in ruminants suggests that reduced-oil may has less energy value than conventional high-oil DDGS, but energy content is equal to or greater than the energy value of corn. Recent studies for swine and poultry have shown that reduced-oil DDGS sources have slightly reduced amino acid digestibility compared with high-oil DDGS sources, but responses of individual amino acids vary. Furthermore, although amino acid digestibility is generally less in reduced oil DDGS sources, total amino acid content is increased resulting in minimal change in digestible amino acid content among reduced-oil and high-oil DDGS sources (see Chapter 6). No studies have been conducted to compare phosphorus digestibility between reduced-oil and high-oil DDGS sources for poultry and swine.

What is the average protein content of reduced-oil DDGS?

In a recent comprehensive meta-analysis study, Zeng et al. (2017) showed that the average crude protein content of corn DDGS is 27 percent (88 percent dry matter basis) with a coefficient of variation of 8.7 percent (see Chapter 6). Although many DDGS traders and nutritionists expected the crude protein content to slightly increase with partial extraction of corn oil to produce reduced-oil DDGS, this is not a consistent response when comparing protein content among sources.

Is high-protein DDG available in the export market?

Yes. Several new technologies have been implemented in some U.S. ethanol plants to produce high protein corn co-products containing 40 to 50 percent crude protein (see Chapter 5). Limited research is available on the maximum diet inclusion rates and performance responses from feeding these new high protein corn co-products to various species. It is important to realize that the energy and nutrient content, especially the amino acid profile of these new high protein co-products is substantially different than the energy and nutrient content of high protein DDG produced by front-end fractionation processes several years ago. Therefore, although some published studies have shown that feeding high protein DDG produced from front-end fractionation processes results in excellent performance, these results are not directly applicable to the new high-protein co-products currently being produced.

Is DDGS color a reliable indicator of quality and nutritional value of DDGS?

Extremely dark colored DDGS has been shown to reduce digestibility of protein and amino acids, but recent studies have shown a very poor relationship between color and amino acid digestibility among DDGS sources (see Chapter 10). Color is an unreliable and poor indicator of nutritional value because many factors in addition to drying temperature affect color. Therefore, purchasers and nutritionists should not assume that darker-colored DDGS has less nutritional value than lighter-colored DDGS sources.

Can DDGS replace soybean meal in animal feeds?

Each individual feed ingredient is a package of nutrients in various quantities and proportions. The three most expensive nutrients in livestock and poultry feeds are energy, amino acids and phosphorus. Depending on relative ingredient prices, DDGS partially replaces some of the energy, amino acid and phosphorous sources in commercial livestock and poultry diets. In typical corn and soybean diets DDGS partially replaces corn and soybean meal. But where a greater variety of energy and protein sources are available, DDGS may replace other ingredients without reducing the soybean meal in the ration.

The differences between soybean meal and DDGS in swine and poultry rations are:

- The energy value of DDGS is greater than dehulled soybean meal in livestock and poultry diets.
- The protein content of DDGS typically averages about 27 percent whereas soybean meal contains 44 to 48 percent crude protein.
- The amino acids most likely to be limiting in corn-soybean meal based swine and poultry diets are lysine, methionine, threonine and tryptophan. Soybean meal is substantially higher in these essential amino acids, and they are more digestible than in DDGS.
- Soybean meal contains about the same concentration of phosphorus as DDGS, but the majority of the phosphorus in DDGS is in a chemical form that is easily digested and utilized by swine and poultry compared to the indigestible form of phosphorus (phytic acid) found in soybean meal. This nutritional advantage for DDGS allows nutritionists to significantly reduce the amount of inorganic phosphorus supplementation needed in the diet, diet cost and phosphorus concentrations in manure, while supporting optimum swine and poultry performance.

In contrast, several studies have shown that DDGS is an excellent replacement for soybean meal in ruminant diets.

Does DDGS contain mycotoxins?

Most of the corn used to produce DDGS is grown in the upper Midwest of the United States. Depending on the weather conditions during a given crop year, various mycotoxins can be produced during unusual growing conditions that stress the corn plant (e.g. drought, excessive rainfall, extreme high temperature and high humidity). When these growing conditions occur, they are often more isolated in a portion of the major corn production region and not in the entire corn crop. If mycotoxins are present in corn used to produce ethanol and co-products, they are not destroyed during this process and are concentrated by about three times in DDGS. Therefore, most U.S. ethanol plants have implemented maximum standards for the major mycotoxins (e.g. aflatoxins, deoxynivalenol, fumonisins, zearalenone) before accepting incoming corn sources at the ethanol plants. These ethanol plants test incoming loads of corn and reject loads that exceed these standards in order to produce DDGS below these maximum mycotoxin concentrations. In general, recent surveys have shown that the prevalence of various maycotoxins in U.S. corn for a specific year is less than corn produced in Asia, Central and South America.

Does DDGS contain ethanol?

No. The distillation process used in ethanol plants is very complete and, because alcohol is very volatile (evaporates easily), any alcohol remaining is lost during the drying process used to produce DDGS.

Are there antibiotic residues in DDGS?

Small amounts of antibiotics are used to control bacterial infections during corn fermentation to produce ethanol and corn co-products. The two most common antibiotics used are virginiamycin and penicillin. Studies have shown that when these antibiotics are added at recommended doses, they are completely degraded due to the low pH and high temperature conditions used during the production process. Recent research conducted at the University of Minnesota indicated that only about 12 percent of DDGS samples collected in the U.S. ethanol industry contained detectable but very small amounts of one or more antibiotic residues. However, due to the processing conditions used to produce ethanol and DDGS in ethanol plants, these antibiotic residues did not have biological activity. Therefore, even though antibiotics are used in ethanol production, DDGS is safe to feed to animals based on current U.S. Food and Drug Administration regulations.

Why do some DDGS sources contain high sulfur content?

To optimize ethanol production and produce high quality DDGS, ethanol plants need to optimize pH during fermentation. To do this, small amounts of sulfuric acid are used to reduce pH, and as a result, can increase sulfur content in DDGS. The sulfur content can range from 0.6 to 1.0 percent among DDGS sources. Recent studies have shown that feeding diets containing high sulfur content to swine has no negative effects on growth performance and may actually improve antioxidant status of pigs (see Chapter 14). However, feeding high sulfur DDGS sources at high dietary inclusion rates to ruminants can increase hydrogen sulfide production and increase the risk of sulfur toxicity leading to the development of polioencephalmalacia. Furthermore, feeding high sulfur diets to ruminants can reduce dry matter intake, fiber digestibility, and growth performance (see Chapters 14, 17, and 19). Therefore monitoring sulfur content of DDGS is important to avoid exceeding the recommended 0.4 percent of total sulfur in the diet for dairy, beef, sheep and goats.

Can DDGS be safely stored at feed mills for a long-period of time?

There are limited studies that have evaluated the effects of long-term storage of DDGS under various storage times, temperatures, and relative humidity. Corn DDGS has some unique chemical and physical properties compared with other feed ingredients including an ability to attract moisture and relatively high oil content. The ability of DDGS to attract moisture can influence its handling characteristics and potentially increase mold and mycotoxin production if moisture content exceeds 15 percent. The corn oil present in DDGS contains high concentrations of polyunsaturated fatty acids which are susceptible to peroxidation during storage. However, a recent study has shown that adding commercially available antioxidants can be effective in preventing lipid peroxidation in DDGS and distillers corn oil when stored in high temperature and high humidity conditions (see Chapter 9).

Can bridging and caking of DDGS in containers be prevented?

Corn DDGS has some unique chemical and physical properties compared with other feed ingredients that cause it to bridge or cake which reduces flowability. Although some flow agents have been used to prevent flowability problems when transporting DDGS in containers, studies have shown that they are generally ineffective (see Chapter 9). However, studies have shown that minimizing moisture content improves flowability, and reduced-oil DDGS tends to have improved flowability properties compared with traditional high-oil DDGS. It is essential that DDGS be cooled and cured at the ethanol plant for at least 24 hours after being produced before loading to prevent caking and difficult unloading.

How does adding DDGS to poultry, swine and aquaculture feeds affect pelleting and extruding?

The high fiber and low starch content of DDGS has been shown to reduce pellet durability index and pellet mill throughput. However, adjusting pelleting conditions and use of binders can improve pellet quality, mill throughput, and reduce energy use (see Chapters 16, 21, and 24).

How do you determine economic value DDGS in relation to price?

There is a disconnect between the market price of DDGS and the economic value it provides to diets in least cost formulations (see Chapter 2). There are many reasons for this. First, feed ingredients are traded on the basis on minimum guarantees of protein and fat content, but diets are formulated on a metabolizable or net energy, and digestible amino acid basis. Although, protein and fat content are related to energy and digestible amino acid content, using protein and fat content to determine market price underestimates the true economic savings of DDGS in all animal diets. Second, because the energy and protein value of DDGS is greatest in ruminant diets, compared to swine and poultry diets, it also has greater economic value. In fact, studies have shown that there is up to a $60/metric ton greater value for DDGS in swine diets than the purchase price paid in the market. Therefore, the best method of determining DDGS value in various types of livestock and poultry diets is to obtain a complete nutrient profile and the digestibility coefficients of the source being considered, along with the price at which it can be purchased, formulate least cost diets to determine the shadow price at which it will be used in the formula compared with prices of other competing ingredients.

What should be included in the certificate of analyses for DDGS?

Typically, DDGS is traded based on minimum guarantees for crude protein and crude fat, but many traders continue to use the pro-fat combination for nutrient guarantees. The use of pro-fat in DDGS pricing has led to much confusion among traders because the reduction in crude fat content in reduced-oil DDGS does not proportionately increase the crude fat content. Therefore, it is recommended that minimum guarantees for crude protein and crude fat be used instead of pro-fat. However, more DDGS customers are asking for additional guarantees such as minimum mycotoxin concentrations and color scores, beyond moisture, crude protein, crude fat and crude fiber depending upon the intended feeding application. These additional guarantees need to be negotiated between the buyer and seller. In addition, it is extremely important to agree on the commercial laboratory and testing method that will be used for any nutrient analysis being guaranteed or checked because the testing procedure can have a significant influence on whether or not a guarantee is met.

How do I identify a DDGS supplier who can meet my needs?

Due to the variability in processes used by ethanol plants to produce ethanol and DDGS, there can be significant variation in nutrient content and digestibility among sources. This variation in nutrient content and digestibility makes it unwise for nutritionists to formulate diets using typical nutrient values. Therefore, many DDGS users have chosen to contact direct marketers of DDGS, request nutrient information and samples from specific ethanol plants of interest, develop a preferred supplier list of ethanol plants that meet their quality criteria and purchase and use only DDGS from those sources.

CHAPTER 31

U.S. Suppliers of DDGS

Current list of DDGS suppliers is available at www.grains.org.

CHAPTER 32

Glossary of Terms

Absorption	(in animal nutrition) the movement of nutrients from the digestive tract into the blood or lymph system.
Acidosis	an undesirable condition that can occur in ruminant animals when fed diets high in readily fermentable carbohydrates such as starch.
Additive	an ingredient added in small quantities to the diet for the purpose of fortifying it with trace nutrients or medicines.
ADF	Acid detergent fiber. The fraction of a feedstuff that is not soluble in an acidic detergent in a laboratory procedure used to determine some components of fiber.
ADG	Average daily gain. The rate of body weight gain of an animal expressed on a daily basis.
ADICP	Acid detergent insoluble crude protein. A measure of by-pass or ruminally undegradable protein of a feed ingredient.
Adipose	fat tissue in an animal or carcass.
ADIN	Acid detergent insoluble nitrogen. A measure of the insoluble portion of nitrogen in a feed ingredient; used to calculate ADICP.
Ad libitum	(feeding) unlimited access to feed or water.
Aerobic	living or functioning in the presence of oxygen.
Aflatoxin	a carcinogenic mycotoxin produced by molds under specific environmental conditions in growing and stored grains.
Aleurone	the protein portion of the endosperm of a seed.
Amino acids	nitrogen containing organic molecules that are the building blocks of proteins, and essential components of nutrition.
Amylase	an enzyme that can hydrolyze starch to maltose or glucose.
Anaerobic	living or functioning in the absence of oxygen.
Antibiotic	a substance produced by a microorganism that has an inhibitory effect on other microorganisms.
Anti-nutritional factors	chemical components of feed ingredients that reduce the nutritional value of a feed ingredient.
Antioxidant	a substance that prevents fats from becoming rancid through oxidation.
Apparent digestibility	the amount of a nutrient that is absorbed from the gastrointestinal tract.
Arginine	an essential amino acid.

As fed	as consumed by the animal.
Ash	the residue remaining after complete incineration at 500° to 600° C of a feed; comprised of metallic oxides.
Assay	the determination of the chemical components of a feed ingredient or complete feed.
Availability	(nutrient) – the proportion of a nutrient that is utilized by the animal.
Bacteria	single-celled living organisms that multiply by simple division. Some are beneficial while others can cause illness.
Balanced diet	a combination of feed ingredients that provide the essential nutrients in the required amounts to meet the animal's needs.
Barrow	castrated male pig.
Beta-carotene	a precursor source of vitamin A found in some plants and plant products.
Biopsy	the removal and examination of tissue or other material from the living body.
Boar	intact, uncastrated male pig.
Bran	seed coat of cereal grains.
Brewer's grains	a grain co-product of the brewing industry.
Beer	(in ethanol production) – a term that refers to the fermented mash that contains ethanol.
By-pass protein	protein not broken down by microbes in the rumen and available for further digestion in the small intestine.
Calorie	a unit of energy measurement defined as the amount of heat required to raise the temperature of one gram of water from 14.5 to 15.5° C.
Carbohydrates	organic substances containing carbon, hydrogen and oxygen; many different kinds are found in plant tissues and include starch, sugar, cellulose, hemicellulose, pectins and gums.
Carcinogen	substances that can cause cancer.
Carotene	a yellow organic compound that is a precursor for vitamin A.
Cecum	a section of the gastrointestinal tract that follows the small intestine and precedes the large intestine which contains a significant amount of bacteria that break down fiber not digested in the small intestine.
Cellulose	a polymer of glucose that has a linkage between glucose molecules resistant to hydrolysis in pigs and poultry, but can be broken down by microbes in the rumen of cattle and sheep and converted into energy.
Co-product	secondary products produced in addition to principle products.

Co-products, ethanol dry-grind	the water and solids remaining after distillation of ethanol is called whole stillage, comprised primarily of water, fiber, protein and fat. This mixture is centrifuged to separate coarse solids from liquid. The coarse solids are also called wet cake and contain about 35 percent dry matter. Wet cake can be sold to local cattle feeders without drying, or dried to produce dried distiller's grains (DDG). The liquid, now called as thin stillage, goes through an evaporator to remove additional moisture and the resulting co-product is called condensed distiller's solubles which contains approximately 30 percent dry matter. Condensed distiller's solubles can be sold locally to cattle feeders. or, the wet cake can be mixed with condensed distiller's solubles and dried to produce distiller's dried grains with solubles (DDGS) which has 88 percent dry matter.
Colon	the lower portion of the large intestine.
Complete feed	a single feed mixture which may be used as the only source of the nutrients required by an animal except water.
Condense	a process to reduce an item such as stillage to a denser form by removing moisture.
Condensed distiller's solubles	see Co-products, ethanol dry milling.
Corn germ meal	a co-product from wet milling ethanol plants that contains about 20 percent crude protein, 2 percent fat and 9 percent fiber with an amino acid balance that makes it a useful feed ingredient in swine and poultry diets.
Corn steep liquor	a high energy liquid co-product produced in wet milling ethanol plants that is sometimes combined with corn gluten feed or sold separately as a liquid protein source for beef and dairy cattle.
Crude fat	the portion of a feed or feed ingredient that is soluble in ether and is often referred to as ether extract.
Crude fiber	the less digestible portion of a feed ingredient composed of cellulose, hemicelluolose, lignin and other complex carbohydrates.
Crude protein	an estimate of the protein in a feed or feed ingredient, calculated by measuring the nitrogen content (proteins contain about 16 percent nitrogen) and multiplying by a factor of 6.25 to obtain the crude protein percentage.
Cystine	a sulfur containing amino acid that can replace up to 50 percent of the swine requirement for methionine.
DDGS	Distiller's dried grains with solubles. In dry-grind ethanol production, a blend of the wet cake and at least 75 percent condensed solubles, dried to a moisture content of about 10 percent. See Co-products, ethanol dry-grind.
Deamination	removal of the amino group from an amino acid.
Diet	a regulated selection or mixture of feed ingredients provided on a continuous basis or prescribed schedule.
Digestibility	a measure of the extent that the nutrients in a feed are digested and absorbed by an animal.

DE	Digestible energy. Gross energy of the feed minus the energy remaining in feces.
Digestion	the process occurring in the gastrointestinal tract that breaks down complex nutrients into forms that can be absorbed by an animal.
DON	Deoxynivalenol. a mycotoxin sometimes abbreviated as DON and often referred to as vomitoxin because it causes reduced feed intake and feed refusal at low concentrations in the diet and vomiting at higher dietary concentrations.
DL-methionine	a source of synthetic methionine.
Dressing percent	also known as carcass yield and is the portion of the carcass remaining after the removal of most internal organs, feet and in most cases, the head.
Drug	as defined by the U.S. Food and Drug ADMInistration is a substance intended for the use in the diagnosis, cure, mitigation, treatment or prevention of disease in humans and other animals.
Dry grind	refers to an ethanol production process that involves grinding the whole corn kernel and fermenting the resultant corn meal without separating out the component parts.
DM	Dry Matter. The portion of a feed remaining after water is removed by drying in an oven.
Duodenum	the first portion of the small intestine.
Endogenous	(in nutrition) – compounds such as enzymes and hormones that are internally produced by the body.
Endosperm	part of the seed which provides food for the developing embryo.
Enzyme	a protein formed in animal or plant cells that act as biological catalysts to increase the rate of chemical reactions.
Essential amino acid	an amino acid that cannot be synthesized in the body in sufficient quantities for the body’s needs and must be supplied in the diet.
Ether extract	used to measure the amount of fats and oils in feeds and feed ingredients based on their solubility in ether.
Excreta	the products of excretion from an animal’s body which are primarily feces and urine.
Exogenous	(in nutrition) originating from outside of the body.
Fat soluble vitamins	vitamins A, D, E and K (menadione).
Fatty acids	components of a fat molecule that have different carbon lengths and may be unsaturated or saturated.
Feed conversion	the amount of feed required by an animal for a unit of weight gain.
Fermentation	chemical changes brought about by enzymes produced by various microorganisms.
Flowability	the ability of a mass of feed particles or grains to move by gravity out of storage or transport containers.

Fumonisins	a mycotoxin produced by specific molds that can be present in feed ingredients and reduce animal health and performance.
Fractionation	processes used in dry-grind ethanol plants to separate various components of the corn kernel to improve ethanol yield and produce a variety of co-products with different nutritional composition.
Gain:Feed	
Gastric	refers to the stomach of animals.
Gastrointestinal	refers to the stomach and the rest of the intestinal tract used in digestion and absorption of nutrients.
GE	Gross energy. The total heat of combustion of a feed or feed ingredient burned in a bomb calorimeter.
Germ	the embryo of a seed.
Glycerol	a three carbon component of fat.
Ground, grinding	a mechanical process to reduce particle size by impact, shearing or attrition.
Hulls	the outer covering of seed kernels.
Hydrogenation	the chemical addition of hydrogen to any unsaturated compound (double bond), often to fatty acids.
Hydrolysis	the chemical process where a compound is split into simpler units with the uptake of water.
Ileum	the lower portion of the small intestine.
IU	International units. An arbitrary scale used to compare the biological activity of some vitamins.
Insoluble fiber	the portion of non-starch polysaccharides that is not easily fermented in the lower intestinal tract of animals
In vitro	refers to things that occur outside the animal's body in an artificial environment such as a test tube. In vivo – refers to things that occur within the animal's body.
Iodine number	the amount of iodine (in grams) that can be taken up by 100 grams of fat or fatty acids and is a measure of unsaturation.
Jejunum	the middle portion of the small intestine.
Kcal (kilocalorie)	is a unit of energy equal to 1,000 calories.
Kjeldahl	a method to determine the nitrogen content of a feed ingredient to be used in calculating and estimating crude protein.
Lesion	an unhealthy change in color, size or structure of body tissues.
Lignin	an indigestible inorganic component of fiber.

Linoleic acid	an essential fatty acid.
Lipid	fat.
Liquifaction	the process of converting solids into liquid.
Macro (major) minerals	minerals present or required in large amounts relative to the animals requirement and include (calcium, phosphorus, sodium, potassium, magnesium, sulfur and chloride).
Maillard products	a group of poorly digestable protein-carbohydrate complexes that are produced in feed ingredients that are subjected to significant amounts of heating and are characterized by darkening of color (browning), burned flavor and burned smell.
Mash	a mixture of water and corn meal prior to fermentation in a dry grind ethanol plant.
Meal	a grain or feed ingredient or diet that has been ground or otherwise reduced in particle size.
Megacalorie	Mcal. unit of energy equal to 1,000,000 calories or 1,000 kilocalories.
Metabolism	the net effect of biochemical changes in the body including building up (anabolism) and breaking down (catabolism).
ME	Metabolizable energy. Gross energy minus fecal and urinary energy from feeding a complete feed or feed ingredient.
Micro (trace) minerals	minerals present or required in small amounts in feeds and feed ingredients relative to the animal's requirement and include (iron, copper, zinc, iodine, selenium and manganese).
Modified wet cake	a blend of partially dried wet distiller's grains with condensed distiller's solubles which has dry matter of approximately 50 percent. See also Co-products, ethanol dry milling.
Monogastric	refers to animals such as swine and poultry that have a single, simple stomach.
Mycotoxicosis	poisoning of an animal that occurs when consuming significant quantities of mycotoxins.
Mycotoxins	toxic substances produced by specific types of molds under specific types of climatic and environmental conditions.
NDF	Neutral detergent fiber. fiber components in plant and grain cell walls that is undigestible for monogastric animals.
NE	Net energy. metabolizable energy minus the heat increment.
NFE	Nitrogen free extract. A calculated estimate of the carbohydrate fraction of a feed ingredient by subtracting moisture, fat, fiber, protein and ash from 100 percent.
NPN	Non-protein nitrogen. Any one of a group of nitrogen containing compounds that are not true proteins that can be precipitated from a solution (e.g. ammonia and urea).
Nutrient	any chemical substance that provides nourishment to the body.
Ochratoxin	a mycotoxin produced by aspergillus mold which attacks the kidneys, reduces growth performance and may cause birth defects.

Oleic acid	an 18 carbon fatty acid that contains one double bond and is found in animal and vegetable fat.
Oxidation	the union of a substance with oxygen.
Palmitic acid	a saturated fatty acid with 16 carbons.
pH	a measure of the acidity or alkalinity of a substance; pH of 7 is neutral.
Phytic acid	alternative chemical forms of phytate or phytin and are naturally occurring bound phosphorus compounds in grains and grain co-products that have low digestibility and availability for monogastric animals.
Phytase	is a commercially available enzyme added to monogastric diets to improve digestibility of phosphorus in the phytic acid form in grains and grain co-products for monogastric animals.
ppm	Parts per million. A unit of concentration for compounds found in small amounts in feeds and feed ingredients and is equal to mg/kg.
Premix	a mixture of the proper proportions of vitamins and trace minerals that when added to animal diets will meet the requirements for those nutrients.
Propionic acid	one of the volatile fatty acids commonly found in rumen contents.
Proximate analysis	a combination of analytical procedures used to describe feeds and feed ingredients.
Rancid	a term used to describe fats that have undergone partial decomposition.
Ration	a fixed portion of feed, usually expressed as the amount of a diet allowed daily.
Rumen	the second compartment of a ruminant stomach.
Ruminant	any group of hoofed mammals that have a four compartment, complex stomach and that chew their cud while ruminating.
Rumination	the process of regurgitating previously eaten feed, reswallowing the liquids and rechewing the solids (cud).
RUP	Ruminally undegradable protein. Sometimes referred to as by-pass protein, which is protein that is not degraded by microbes in the rumen and enters the small intestine of ruminants. Generally, undegradable protein is heat damaged protein.
Saccharification	is a process involving hydrolysis (break down) of starch using water and enzymes in ethanol production.
Saturated fat	a fat that contains no fatty acids with double bonds and is solid at room temperature.
Silage	feed resulting from storage and fermentation of wet crops under anaerobic storage conditions.
Soluble fiber	the portion of non-starch polysaccharides in a feed that is readily fermented by microbes in the lower intestinal tract of animals

Solubles	(syrup). In drymill ethanol production, the liquid portion of stillage separated from the coarse grain by centrifugation and concentrated to about 30 percent solids by evaporation. See Co-products, ethanol dry milling.
Starch	a white, tasteless, odorless polysaccharide carbohydrate found in large quantities in corn, sorghum, wheat and other grains that yields glucose upon hydrolysis.
Steeping	in wetmill corn processing, a process that involves soaking corn kernels under controlled conditions for temperature, time and concentration of sulfuric acid and lactic acid to soften the corn kernel before separating the germ, bran, gluten and starch in wet milling ethanol production.
Stillage	see Co-products, ethanol dry milling.
Stomach	the part of the digestive tract where chemical digestion is initiated in most animal species.
Syrup	see Co-products, ethanol dry milling.
TDF	Total dietary fiber. A measure of non-starch polysaccharides in a feed or feed ingredient and includes soluble and insoluble fiber
TDN	Total digestible nutrients. A value that indicates the relative energy value of a feed for an animal.
Trace minerals	see micro minerals.
Ulcer	erosion or disintegration of stomach tissue.
Unsaturated fat	a fat containing from one to three fatty acids that contain one or more double bonds.
Urea	a synthetic, highly concentrated nitrogen product sometimes used as a nitrogen source in rations for ruminants.
VFA	volatile fatty acids which include propionic, acetic and butyric acids.
Volatile fatty acids	short chain fatty acids produced in the rumen of cattle and the cecum and colon of monogastrics that provide energy value to the animal.
Wet cake	see Co-products, ethanol dry milling.
Wet distiller's grains	see Co-products, ethanol dry milling.
Wet milling	processes used to separate various components of the corn kernel into associated fractions including high fructose corn syrup, corn oil, starch and fiber.
Zearalenone	a mycotoxin produced by fusarium molds under specific climatic and environmental conditions; it has estrogenic effects, causing reproduction problems in animals.

CHAPTER 33

Website Links

- U.S. Grains Council:
  http://www.grains.org

- Distillers Grains Technology Council:
  http://www.distillersgrains.org/grains/

- National Corn Growers Association (NCGA):
  http://www.ncga.com/

- Renewable Fuels Association (RFA):
  http://www.ethanolrfa.org/

- Ethanol Producer Magazine:
  http://www.ethanolproducer.com

- The Online Distillery Network:
  http://www.distill.com/offlinks.html

- University of Minnesota:
  http://www.ddgs.umn.edu/

- United States Department of Agriculture, Foreign Agriculture Service (FAS):
  http://www.fas.usda.gov/ustrade/
  http://www.fas.usda.gov/

CHAPTER 34

Key Review Articles and Additional Reading

Research Reviews

General

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Dairy

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