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	Renukdas et al., 20141
Varied among experiments	0 - 40	soybean meal	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 was decreased	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	Whole body fat 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 decreased and 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	Renukdas et 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, 18:2*n*-6, and 20:1*n*-9 increased, and concentrations of 14:0, 16:1*n*-7, 18:1*n*9, 18:3*n*-3, 20:5*n*-3, 22:5*n*-3 and 22:6*n*-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	soybean meal, corn starch	56	6	0 - 0.13	40	Rhodes et al, 2015[1]
0.99 - 6.1	0 - 30	fish meal, soybean meal, wheat flour	56	0	0 - 0.4	Partial replacement of soybean meal with DDGS in diets containing no fish meal reduced growth performance	Cummins et al., 2013
0.04 - 16.3	10	sorghum	126	0	none	10	Sookying and 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	Sunflower meal, rapeseed meal, 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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