DISTILLERS DRIED GRAINS WITH SOLUBLES AS AN ALTERNATIVE PROTEIN SOURCE IN FISH FEEDS

CHHORN LIM AND MEDIHA YILDIRIM-AKSOY

Aquatic Animal Health Research Unit, Agricultural Research Service, U.S. Department of Agriculture, 990 Wire Road, Auburn, Alabama 36832, USA
Email: chhorn.lim@ars.usda.gov

Abstract

Distillers dried grains with solubles (DDGS), a co-product of the dry-mill ethanol industry, are the dried residue that remains after the fermentation of corn (or other grains) mash by selected yeasts and enzymes to produce ethanol and carbon dioxide. The nutrient composition of DDGS varies depending on the source of grain and the methods used for ethanol and DDGS production. Generally, corn DDGS contains approximately 29% crude protein, 10% fat, 9% crude fiber and 5% ash. Based on the essential amino acid (EAA) composition, distillers grain products (DGP) from various grain sources are deficient in a few EAA for most fish species, notably in lysine and methionine but does not contain anti-nutritional factors found in most other plant protein sources. At present, DGP are mainly used in terrestrial animal feeds, and its use in fish feeds is limited. Optimum inclusion levels of DDGS in fish diets appeared to vary depending on the type of ingredient substituted and levels of other protein source, especially fish meal, present in the diets. However, results of previous research have shown that corn DDGS is a promising ingredient for aquaculture diets. A level of 20 to 40% DDGS has been successfully used in channel catfish and tilapia diets. In trout diets, a level of 15% has been suggested. However, inclusion levels of dietary DDGS can be increased by supplementation of limiting EAA such as lysine.

INTRODUCTION

Aquaculture is the fastest food producing sector in the world, expanding at a rate of 9%/year over the past 10 years. The rapid expansion of the aquaculture industry, along with the improvement and change in culture techniques, have increased the demand for fish feeds. Global production of aquafeeds was approximately 19.5 million metric tons (Mmt) in 2003 and is expected to increase to more than 39 Mmt by the end of the decade (Hardy 2008). Fish meal, because of its high protein content, balanced amino acid profile, high digestibility and palatability and as a source of n-3 highly unsaturated fatty acids, has traditionally been used as the major protein source in fish feeds. This is particularly the case of diets of carnivorous species, such as salmonids. According to the International Fish Meal and Fish Oil Organization, global fish meal production is relatively constant, between 5 and 7 million metric tons (Mmt), since 1989 and the outlook for the future has been predicted to be similar to the past. This trend, coupled with the increased demand of fish meal for aquafeeds and the increased competition among other consumer segments such as the husbandry of pets and livestock, has dramatically increased the price of fish meal in recent years. It is likely that the price of fish meal will remain higher than the normal range for the foreseeable future. This development presents formidable challenges for fish nutritionists to reduce the dependence of aquaculture diets on fish meal, increase the use of conventional alternative protein sources, as well as to look for other low-cost alternative sources of protein. Distillers dried grains with solubles (DDGS), a major by-product of the dry mill ethanol industry, is currently readily available and competitively priced (on a per unit protein basis) relative to other conventional alternative protein sources. According to Renewable Fuels Association, the U.S. production of DDGS reached 14.6 million ton in 2007, which is more than five times that produced in 2000. DDGS derived from corn has a relatively high protein and fat content (approximately 29 and 10%, respectively) and does not contain anti-nutritional factors found in most plant protein sources. At present, the use of DDGS in aquaculture diets is limited, however, recent research has shown that DDGS is a promising alternative feed ingredient for several fish species such as rainbow trout (*Oncorhynchus mykiss*), channel catfish (*Ictalurus punctatus*) and tilapia (*Oreochromis* spp.).

This paper provides an overview of the physical characteristics, nutrient composition of DDGS from different grains and use of corn DDGS in diets of various aquaculture species. The nutritional value of various DDGS will also be assessed based on their essential amino acid (EAA) content and the EAA requirements of fish.

PHYSICAL CHARCTERISTICS OF DDGS

Corn DDGS is a free-flowing granular product with color ranging from yellow/tan to brown and a bulk density of 13.8 to 17.8 kg per cubic foot.. It was previous believed that color there was no correlation between the color and nutritional value of DDGS. However, recent research results with swine and poultry (Cromwell at al. 1993; Fastinger *et al.* 2006) showed lower nutritional value of dark-colored DDGS. The dark brown color was a result of overheating during the drying process leading to binding and/or destruction of nutrients such as lysine.

CHEMICAL COMPOSITION

DDGS is a byproduct produced by dry mill ethanol plants after yeast fermentation of starch from cereal grains to produce ethanol and carbon dioxide. In the United States, most of the ethanol produced is made from corn. Each 2.54 kg of corn fermented in a dry-mill ethanol plant produces about 1.02 L of ethanol, 0.28 kg of carbon dioxide and 0.82 kg of DDGS. Because corn contains about two-thirds starch and most starch is converted to ethanol during fermentation, the nutrient (protein, fat, fiber, ash and phosphorus) content of DDGS are 2 to 3 times more concentrated than in corn. Thus, the chemical composition of DDGS varies with the sources and quality of grain used to produce ethanol. There can be a large variation in the nutrient content and quality of DDGS produced in different plants. Product variability also exists within a plant due for example to fermentation time and efficiency, the quantity of distillers solubles added to distillers grains and the drying process employed.

Proximate Composition

Proximate composition of representative distillers products from various grains are presented in Table 1. Distillers grain products (DGP) have very low concentrations of starch because most of the starch in the grain is converted to ethanol. The crude protein and fat contents of DDGS, distillers dried grains (DDG), and distillers dried solubles (DDS) from corn were similar. Compared with DDG, DDS has lower crude fiber content but higher ash. The values of crude fiber and ash content of DDGS were approximately average of those of DDG and DDS, as expected.

Although corn is the major grain used in alcohol production, wheat, barley and sorghum (milo) may also be used. DDGS from wheat has higher protein (44%) and lower fat content (3.5%) than distillers products from corn and sorghum. Sorghum and barley-based DDGSs have slightly lower crude protein and fat (no data for barley DDG), but similar in ash content compared to those of corn-based DDGS.

Table 1. Proximate composition (% dry matter) of different distillers grain products (DGP)

Proximate composition (% dry matter)						
Distillers gains products						
	Corn[1]			Wheat[2]	Sorghum[3]	Barley[4]
	DDGS	DDG	DDS	DDGS	DDGS	DDG
Dry matter	92	92	92	92	90.4	87.5
Crude protein	29.4	29.4	29.4	44	26.6	28.7
Crude fat	9.8	9.8	9.8	3.5	8.1	--
Crude fiber	9.2	14.1	4.9	7.9	--	--
Ash	4.9	2.4	8.9	5.9	4.9	--

[1]Feedstuffs (2008)
[2]Dong *et al.* (1987)
[3]Hancock *et al.* (1995)
[4]Consisted of 65% barley, 35% corn (Weiss *et al.* 1989).

Essential amino Acid (EAA)

The EEA composition of DGP is also influenced by type of grain used. The EAA content of DDGS, DDS and DDG from corn, and DDGS from wheat, sorghum and barley, dehulled solvent-extracted soybean meal (SBM) and menhaden fish meal (FM) is given in Table 2. Due to lower protein content, the concentrations of EAA of DGP from corn, wheat, sorghum and barley, expressed as percent of dry matter, are considerably lower than that of SBM or FM. When expressed as percentage of crude protein, leucine content of DDGS from corn and sorghum is higher than both SBM and FM. Except barley, DDGS contain higher levels of methionine than SBM, but lower than FM. Sorghum-based DDGS also contains a higher level of phenylalanine than SBM or FM. Among the ten EAA, lysine is the most limiting EAA in DDGS from various grain sources, compared to SBM and FM

Vitamins and minerals

Vitamin and mineral contents of corn-based distillers products are given in Table 3. Vitamin and mineral concentrations vary greatly among corn-based distillers products. DDS and DDG contain the highest and the lowest concentrations of most vitamins and mineral, respectively, except vitamin A, sodium and sulfur, which are higher in DDG. The values are intermediate for DDGS. Compared to the vitamin content of SBM (data not shown), corn DGP contains higher levels of niacin, riboflavin and vitamin E.

Nutritional value of distillers grain products (DGP)

The nutritional value of protein sources, commonly know as protein quality, is generally assessed based on the EAA content, as well as their digestibility or bioavailability. Others nutrients such as lipids and carbohydrates also affect nutrient bioavalability. The presence of anti-nutritional factors such trypsin inhibitors in SBM, gossypol in cottonseed mea (CSM) and glucosinolates in rapeseed/canola meal can negatively influence fish performance. DGP do not contain anti-nutritional factors commonly found in most plant protein sources.

Except for the study in rainbow trout by Cheng and Hardy (2004a) who evaluated the apparent digestibility of diets containing 30% corn DDGS combined with 70% of a casein-gelatin-based diet and supplemented with various levels of microbial phytase, no studies have determined nutrient digestibility of DDGS in fish. They reported that the apparent digestibility of EAA in these diets were high and ranged from 87.9 to over 90%. Supplementation of phytase (300 FIU/kg diet) improved the digestibility of several EAA, although the absolute differences were small. However, since data on the digestibility of EAAs in DDGS for catfish and tilapia are not available, EAA content is used to assess their nutritional value of DDGS for these species.

Table 2. Essential amino acid (EAA) composition of different distillers grain products (DGP), dehulled, solvent-extracted soybean meal (SBM) and menhaden fish meal (FM).

EAA	Percent composition[1]							
	Distillers grains products						SBM[2]	FM[2]
	Corn[2]			Wheat[3]	Sorgum[4]	Barley[5]		menhaden
	DDGS	DDG	DDS	DDGS		DDG	solvent	
Arginine	1.19 (4.07)	1.09 (3.71)	1.09 (3.71)	2.46 (5.59)	0.97 (3.65)	1.81 (6.31)	4.09 (7.53)	3.97 (5.89)
Histidine	0.68 (2.33)	0.65 (2.21)	0.65 (2.21)	1.17 (2.66)	0.57 (2.14)	0.33 (1.15)	1.48 (2.72)	1.65 (2.45)
Isoleucine	1.09 (3.70)	1.01 (3.44)	1.30 (4.42)	1.70 (3.86)	0.99 (3.72)	0.82 (2.86)	2.95 (5.44)	2.67 (3.87)
Leucine	3.04 (10.37)	2.83 (9.63)	2.28 (7.76)	3.35 (7.61)	2.55 (9.59)	2.10 (7.32)	4.32 (7.95)	4.78 (7.10)
Lysine	0.87 (2.96)	0.98 (3.33)	0.98 (3.33)	1.24 (2.81)	0.60 (2.26)	0.39 (1.36)	3.43 (6.32)	5.11 (7.58)
Methionine	0.55 (1.89)	0.49 (1.67)	0.65 (2.21)	0.67 (1.53)	0.46 (1.73)	0.29 (1.01)	0.80 (1.46)	1.85 (2.74)
Phenylalanine	1.30 (4.44)	0.65 (2.21)	1.63 (5.54)	2.30 (5.22)	2.02 (7.59)	1.15 (4.01)	3.07 (5.65)	2.48 (3.68)
Threonine	1.00 (3.41)	0.33 (1.12)	1.09 (3.71)	1.30 (2.96)	0.87 (3.27)	0.99 (3.45)	2.27 (4.18)	2.99 (4.44)
Tryptophan	0.22 (0.74)	0.23 (0.78)	0.22 (0.75)	0.47 (1.07)	0.22 (0.83)	NA	0.80 (1.46)	0.54 (0.81)
Valine	1.45 (4.93)	1.30 (4.42)	1.74 (5.92)	2.22 (5.04)	1.25 (4.70)	1.10 (3.83)	3.07 (5.65)	3.04 (4.52)

[1]Values are expressed as percent of dry matter. Numbers in parenthesis are percent of crude protein.
[2]Feedstuffs (2008).
[3]Dong *et al.* (1987)
[4]Hancock *et al.* (1995)
[5]Consisted of 65% barley, 35% corn (Weiss *et al.* 1989).

Table 3. Vitamin and mineral content of three corn distillers products: distillers dried grains (DDG), distiller dried grains with solubles (DDGS) and dried distillers solubles (DDS).

Vitamins (IU or mg/kg)	Corn distillers products[1]		
	DDG	DDGS	DDS
A (IU)	3100	2700	1200
D	--	--	--
E	30.5	40	55.8
B_{12}	--	--	--
Thiamin	1.6	3.5	5.9
Riboflavin	2.8	9.0	11.4
Folic acid	--	0.88	1.1
Niacin	42.2	79.9	120
Pantothenic acid	5.9	11.4	21.8
Pyridoxine	--	--	--
Biotin	0.4	0.3	1.1
Choline	1850	3400	4818
Minerals			
Sodium (%)	0.25	0.2	0.18
Potassium (%)	0.16	1.0	1.74
Chloride (%)	0.07	0.17	0.25
Magnesium (%)	0.2	0.42	0.64
Sulfur (%)	0.43	0.3	0.37
Manganese (mg/kg)	23	30	74
Iron (mg/kg)	300	300	600
Copper (mg/kg)	30	50	83
Zinc (mg/kg)	55	85	85
Selenium (mg/kg)	0.35	0.35	0.33

[1]Feedstuffs (2008).

Comparing the EAA in DDGS and EAA requirements of channel catfish (Table 4) and Nile tilapia (Table 5), DDGS is severely deficient in lysine and methionine for both species, regardless of the grain sources used. Corn-based DDGS is also marginally deficient in phenylalanine for channel catfish. Barley-based DDGS, in addition to lysine and methionine, is also deficient in histidine and phenylalanine, while sorghum DDGS is deficient in arginine for channel catfish. For Nile tilapia, tryptophan, threonine and/or histidine are also deficient in DDGS derived from different grain sources.

Assessment of the nutritional value of DDGS based on EAA content is of little significance because nutrient digestibility of DGP, even derived from the same raw material, is greatly influenced by processing conditions prior to or after fermentation processes to produce ethanol. Differences in drying process can result in large variation in the nutritional value of DGP, especially lysine digestibility. Parson *et al.* (1992) reported that excessive heat applied during the drying process may cause Millard reactions that affect the lysine residues and carbohydrate moieties, resulting in darkening of the color of the DGP. Depending on the extent of heating, some lysine may be converted to some compounds or irreversibly bound to a carbohydrate moiety, thus reducing the total lysine content and bioavailability of the products. Fastinger *et al.* (2006) also showed a reduction in the digestibility of lysine as well as other EAA and energy by roosters in the darkest color DDGS.

Use of DDGS in Fish Diets

Although the use of DGP in aquaculture diets has increased recently, DDGS has been used in fish feeds since the late 1940s. The inclusion levels, however, have been relatively low. Phillips (1949) formulated a diet for rainbow trout that contained an equal mixture of plant ingredients (wheat middlings, cottonseed meal (CSM), FM, and DDGS) and beef liver or spleen. Sinnhuber (1964) reported that Oregon moist pellets fed to salmonids contained 3% DDGS. Phillips *et al.* (1964) reported that feeding a dry diet containing 24% FM, 5% CSM, 10% brewer's yeast, and 21% DDGS provided growth in brown trout (*Salmo trutta*) similar to that of fish fed meat-meal mixtures. Also this was the first dry diet to provide viable trout eggs in female broodstocks with 86% total hatching rate and 88% survival to the eyed stage. Previously, broodstock fed a dry diet resulted in egg hatching rates of only 4 to 5%. Hughes (1987) found that 8% DDGS can be included in lake trout (*Salvelinus namaycush*) diets. Robinette (1984) suggested an inclusion level of 7.5% DDGS in a 36% protein diet for channel catfish fingerlings. Deyoe and Tiemeire (1969) indicated that 10% DDGS can be incorporated in a 25% protein diet for channel catfish.

Table 4. Essential amino acid (EAA) requirements (% of dietary protein), amino acid content (% of protein) of DDGS from different grains and percentage of EAA requirement met by these distiller grain products for channel catfish.

EAA	Distillers' grains			Wheat-white		Sorghum-bronze		Barley-based	
	Requirement[1]	Corn							
		% EAA /protein[2]	% of requirement	% EAA /protein[3]	% of requirement	% EAA /protein[4]	% of requirement	% EAA /protein[5]	% of requirement
Arginine	4.3	4.07	95	5.59	130	3.65	85	6.31	147
Histidine	1.5	2.33	155	2.66	177	2.14	143	1.15	77
Isoleucine	2.6	3.70	142	3.86	148	3.72	143	2.86	110
Leucine	3.5	10.37	296	7.61	217	9.59	274	7.32	209
Lysine	5.1	2.96	58	2.81	55	2.26	44	1.36	27
Methionine	2.3[a]	1.89	82	1.53	67	1.73	75	1.01	44
Phenylalanine	5.0[b]	4.44	89	5.22	104	7.59	152	4.01	80
Threonine	2.0	3.41	171	2.96	148	3.27	164	3.45	173
Tryptophan	0.5	0.74	148	1.07	214	0.83	166		
Valine	3.0	4.93	164	5.04	168	4.70	157	3.83	128

[1]Lim *et al.* (2008).
[2]Feedstuffs (2008).
[3]Dong *et al.* (1987)
[4]Hancock *et al.* (1995)
[5]Consisted of 65% barley, 35% corn (Weiss *et al.* 1989).
[a]Includes cysteine
[b]Includes tyrosine

Table 5. Essential amino acid (EAA) requirements (% of dietary protein), amino acid content (% of protein) of DDGS from different grains and percentage of EAA requirement met by these distiller grain products for Nile tilapia.

EAA	Distillers' grains			Wheat-white		Sorghum-bronze		Barley-based	
	Requirement[1]	Corn							
		% EAA /protein[2]	% of requirement	% EAA /protein[3]	% of requirement	% EAA /protein[4]	% of requirement	% EAA /protein[5]	% of requirement
Arginine	4.20	4.07	97	5.59	133	3.65	87	6.31	150
Histidine	1.72	2.33	135	2.66	155	2.14	124	1.15	67
Isoleucine	3.11	3.7	119	3.86	124	3.72	120	2.86	92
Leucine	3.39	10.37	306	7.61	224	9.59	283	7.32	216
Lysine	5.12	2.96	58	2.81	55	2.26	44	1.36	27
Methionine	2.68[a]	1.89	71	1.53	57	1.73	65	1.01	38
Phenylalanine	3.75[b]	4.44	118	5.22	139	7.59	202	4.01	107
Threonine	3.75	3.41	91	2.96	79	3.27	87	3.45	92
Tryptophan	1.00	0.74	74	1.07	107	0.83	83		
Valine	2.80	4.93	176	5.04	180	4.70	168	3.83	137

[1]Lim and Webster (2006).
[2]Feedstuffs (2008).
[3]Dong *et al.* (1987)
[4]Hancock *et al.* (1995)
[5]Consisted of 65% barley, 35% corn (Weiss *et al.* 1989).
[a]Includes cysteine
[b]Includes tyrosine

Catfish

Results of a recent research by Lim *et al.* (2008) suggested that, with lysine supplementation to a level equal to that of the control diet, at least 40% of DDGS can be included in the diet of juvenile channel catfish as a replacement of a combination of SBM and corn meal (CM) without affecting the growth performance, feed utilization efficiency and survival. Whole-body protein and ash content of fish were not influenced by dietary levels of DDGS; however, fish fed diets containing DDGS had increased body fat. They suggested that, since diets used in this study were isonitrogenous, isocaloric and contained approximately the same lipid level, the higher whole-body fat content in fish fed diets containing DDGS may be due to improved diet digestibility leading to higher available energy. In pond studies, Robinson and Li (2008) also showed that 40% DDGS and supplemental lysine can be included in the diet of catfish grown in ponds as a replacement of 36% SBM without affecting weight gain. In the same study, they obtained better weight gain of catfish fed the diet containing 30% DDGS plus supplemental lysine as a replacement of 30% SBM than fish fed the control diet or the diet in which all SBM was replaced by 19% DDGS and 44% CSM plus lysine. They observed that fillet fat was higher or tended to be higher in catfish fed diets containing SBM and DDGS plus supplemental lysine as compared to the group fed the SBM-control diet. This was possibly due to higher energy content the DDGS-containing diets as dietary lipid levels were not adjusted.

Earlier studies also showed that DDGS can be successfully used to replace a portion of SBM in channel catfish diets. Lovell (1980) reported that, when used in combination with 10% fish meal, up to 30% DDGS can be used in channel catfish diets. Likewise, in a cage study, Webster *et al.* (1993) found that 30% DDGS (the highest level tested) can be used as a replacement of a mixture of SBM and CM in channel catfish diets containing 8% fish meal. Other studies by Tidwell *et al.* (1990) and Webster *et al.* (1991) found that, in diets containing 8 to 10% FM, 40% and 35% DDGS, respectively, can be used in catfish diets as substitutes for the combination of SBM and CM on an equal protein basis without requiring lysine supplementation. However, a diet containing 70% DDGS appeared to be deficient in lysine since supplementation of lysine at a level to meet lysine requirement improved the growth of catfish (Webster *et al.* 1991). In another study to evaluate a fixed percentage of DDGS (35%) and a variable percentage of SBM (35-49%) as a partial or total replacement of fish meal in channel catfish diets, Webster *et al.* (1992a) found that the weight gain of fish fed the diet with 0% FM, 35% DDGS and 49% SBM was similar to that of the diet with 12% fish meal and 48% SBM. However, they observed a trend of decreasing growth in fish fed diets with 0 and 4% FM as compared to those of fish fed diets with 12 and 8% fish meal. Improved weight gain was obtained when the 0% fish meal-diet was supplemented with lysine.

Tilapia

Wu et al (1996), in a study to evaluate the growth performance of Nile tilapia fry fed all-plant protein diets reported that, in diets containing 32, 36 and 40% crude protein, incorporation of 16-49% DDGS (in combination with corn gluten meal and corn gluten feed) resulted in good weight gain, and feed and protein efficiencies. In a subsequent 8-week feeding study, tilapia fry were fed diets containing 28 and 32% protein with 63 to 82% DDGS in combination with soy flour, corn gluten meal or corn gluten feed and with and without supplementation of synthetic lysine and tryptophan (Wu *et al.* 1997). They reported that among the 28% protein diet, the best weight gain was obtained from diets containing 67% corn gluten feed and 26% soy flour, and 77.75% DDGS, 15% soy flour with lysine supplementation. In juvenile hybrid tilapia (*O. niloticus* x *O. aureus*), Coyle *et al.* (2004) obtained lower weight gain, specific growth rate (SGR) and feed efficiency ratio (FER) in fish fed diets containing 30% DDGS in the absence of FM or meat and bone meal than fish the fed control diet (0% DDGS) or 30% DDGS diets with 8% fish meal or 26% meat and bone meal. In juvenile Nile tilapia, (Lim *et al.* 2007) using graded levels of DDGS (0, 10, 20, 40 and 40% +lysine) as replacements of SBM-CM combination showed that fish fed diet containing 40% DDGS without the addition of lysine had significantly reduced weight gain, and feed and protein efficiency relative to those obtained with diets containing lower DDGS levels (0, 10 and 20%). The decreased performance of the 40% DDGS-diet was attributed to a deficiency of lysine since supplementation with 0.4% lysine hydrochloride improved weight gain and feed efficiency to levels comparable to those of the SBM-based control diet. They observed that, except for protein content in fish fed the 40% DDGS-diet without lysine supplementation that was significantly lower than that fed the SBM-based diet, whole proximate body composition was not affected by dietary levels of DDGS. The decreased protein content in fish fed the 40% DDGS-diet without lysine supplementation was attributed to smaller-size fish which has less flesh and/or the imbalance of dietary essential amino acids such as deficiency of lysine, which may contribute to reduced protein synthesis. A more recent study by Shelby *et al.* (2008), weight gain, feed efficiency of Nile tilapia fed diet containing 60% DDGS without added lysine were lower compared with SBM-based control diet and diets containing lesser amount of DDGS (0, 30 and 30% + lysine). The addition of lysine to the 60% DDGS diet improved weight gain and FER to levels that were not statistically significant from the control, suggesting that, with lysine supplementation, 60% of DDGS may be incorporated in tilapia diets.

Rainbow trout

Chen and Hardy (2004b) fed rainbow trout a FM control diet (30% herring FM) in diets in which 25, 50 and 75% of fish meal were replaced on an isonitrogenous and isocaloric bases by 7.5, 15 and 22.5% DDGS (and increasing levels of corn gluten meal, CGM) with and without lysine and methionine supplementation. After 6-weeks of feeding, fish fed the diet containing 15% DDGS (replacing 50% of FM) without supplemental lysine and methionine had similar weight gain and feed conversion compared to fish fed the fish meal-based control diet. Increasing DDGS levels to 22.5% significantly decreased weight gain and feed efficiency ratio relative to fish fed the control diet and diets containing 7.5% and 15% DDGS. However, lysine and methionine supplementation improved the nutritional value of the diet containing 22.5% DDGS to a level comparable to that of the control diet. Fish fed the diet containing 15% DDGS with supplemental lysine and methionine had the highest apparent protein retention. This suggests that DDGS can be added up to 15% of diet as a replacement of 50% fish meal in rainbow trout diet without requiring lysine and methionine supplementation. With lysine and methionine supplementation, inclusion level of DDGS can be increased to 22.5% as a substitute of 75% of dietary fish meal. Fish body moisture decreased, but crude fat increased as DDGS levels in diets increased. However, whole body crude protein and ash contents were not affected by dietary levels of DDGS. At the same laboratory, Stone *et al.* (2005) investigated the effects of diet processing methods (cold-pelleted vs. extruded) on diets containing increasing levels of a combination of corn DDGS and corn gluten meal (CGM) as replacements of 0, 25, 50 and 75% FM in diets of rainbow trout. Their results suggest that up to 18.4% corn products (10% DDGS and 8.4% CGM) can be used as a replacement of 25% of the FM without negatively affecting growth performance. Beyond this level, growth of rainbow trout was decreased. Extrusion of diets containing corn products did not improve fish growth compared to fish fed cold-pelleted feeds.

ADDITIONAL ATTRIBUTES OF DDGS

DDGS contain substantial amount of yeast. Ingledew (1999) estimated that 3.9% of total biomass of DDGS was yeast, with 5.3% of the protein content of this product being contributed by yeast. Yeasts are also rich in protein, B-complex vitamins and β-glucan. β-glucan, either in purified form, as a yeast by-product or as live yeast have been reported to stimulate immune responses in human and animals, including fish. Lim at al. (2008) observed that dietary inclusion of DDGS also improved serum total immunoglobulin and antibody titers against *Edwarsiella ictaluri*, although the optimum levels varied among parameters evaluated. Preliminary data on bacterial challenge showed a delayed and reduced cumulative mortality 21 days post-infection challenge with *E. ictaluri* in fish fed DDGS containing diets (10 to 40% DDGS) compared to the control group. In contrast, Lim *et al.* (2007) reported no significant affect of dietary levels (0, 10, 20 and 40%) of DDGS on immune response and resistance of Nile tilapia infected with *Streptococcus iniae*. They suggested, however, that the stimulatory effect of dietary DDGS on immune parameters and resistance of fish to infectious pathogens needs further investigations. More research is also needed to identify compounds in DDGS that have immunostimulatory effect and improve the resistance of fish to pathogens.

Studies in channel catfish by Robinson and Li (2008) and Lim *et al.* (2008) and Nile tilapia (Lim et al 2007) appeared to indicate that dietary inclusion of DDGS improved feed consumption, feed efficiency and/or growth. Li *et al.* (2008) conducted a study to determine whether the improvement of these parameters was caused by the increased dietary lipid level or by other components present in DDGS. They fed juvenile channel catfish for 9 weeks with an all-plant control diet without DDGS (Diet 1), control diet + oil (total fat level equal to that of the diet with 30% DDGS) (diet 2) and diets containing 30% DDGS (diet 3), 20% high protein dried distillers grains (Diet 4), 10% distillers soluble (DS) (Diet 5) or 10% endosperm distillers solubles (EDS) (Diet 6). They found that increased fat levels in diets containing distillers byproducts is partially responsible for the improvement in diet consumption and FER. The presence of distillers solubles (DDGS, DS and EDS) in the diets appears to further increase diet consumption and FER, as well as improves weight gain over the control diets with or without added fat.

CONCLUSION

The recent increased in the prices of conventional fish feed ingredients and the increased supply of DDGS as a result tremendous growth fuel ethanol production has generated great interest in using DDGS in aquaculture diets. Recent research has shown that corn DDGS can be used as a major ingredient in feeds for omnivores and herbivores such as channel catfish, tilapia and carp. The optimum inclusion levels in diets for channel catfish and tilapia range from 20 to 40%. A level of 15% DDGS appear to be adequate in dies of carnivorous species such as rainbow trout. The variation in the inclusion levels reported could be attributed to a number of factors such as species, fish age or size, source and quality of the test ingredients, composition and nutrient content of the experimental diets, supplementation of limiting nutrients, culture system, feeding management and experimental conditions.

However, more studies to determine nutrient bioavailability of various sources of DGP for various aquaculture species are needed for more accurate determination of their nutritional value, feed formulation and to increase their use in aquaculture diets.

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