JOURNAL OF THE
WORLD AQUACULTURE SOCIETY

doi: 10.1111/jwas.12374

Effects of Varying Levels of High-Protein Distiller's Grains on Growth Performance of Channel Catfish, *Ictalurus punctatus*, and Post-Extrusion Feed Pellet Characteristics

J. H. Tidwell, S. D. Coyle, L. A. Bright[1], and L. Pires

Division of Aquaculture, Kentucky State University, Aquaculture Research Center, 103 Athletic Road, Frankfort, Kentucky 40601, USA

K. A. Rosentrater

Department of Agricultural and Biosystems Engineering, Iowa State University, 3167 NSRIC Building, Ames, Iowa 50011, USA

Abstract

Channel catfish, *Ictalurus punctatus*, remains the USA's largest aquaculture industry. However, in recent years, high feed prices have negatively impacted profitability. Production of ethanol as a biofuel has increased dramatically. Companies have modified their processes to enhance ethanol yield and these modified processes also increase the crude protein content of the byproduct. The object of this study was to evaluate this high-protein dried distiller's grains (HP-DDG) for its suitability in catfish diets. A total of 25 full-sibling channel catfish (7.1 ± 2.3 g) were randomly stocked into each of twelve 260-L polyethylene tanks to achieve 25 fish per tank. The control diet was similar to a commercial formulation. Experimental diets contained 20, 40, or 40% HP-DDG with added lysine (1% of total diet). There were three replicate tanks per diet. Fish were fed to apparent satiation twice daily for 9 wk. Average harvest weights for fish fed the 40% HP-DDG diet without lysine supplementation (57.0 g) were significantly smaller than that for fish fed the control diet (77.7 g). Average harvest weights of fish fed 20% HP-DDG (86.8 g) were significantly greater than that of fish fed either 40% HP-DDG (57.0 g) or 40% HP-DDG + lysine (73.7 g). There were no significant differences in feed conversion ratios or survivals among treatments, which overall averaged 1.1 and 99%, respectively. These data indicate that HP-DDG appears to be a suitable ingredient in channel catfish diets up to at least 20% of the total formulation. Data also indicate that inclusion levels of at least 40% HP-DDG are likely limiting in lysine.

In the USA, over 91% of the seafood consumed is imported (NMFS 2015). This has resulted in a trade deficit in seafood products, which now exceeds US$11 billion (NMFS 2015). However, the channel catfish industry, the largest aquaculture industry in the USA, has been in a period of contraction. Production sold to processing plants decreased 50% from 300 million m.t. in 2003 to 115 million m.t. in 2013. This is because of a combination of factors, including competition from lower-priced imports and increases in feed cost. Feed costs represent >50% of the variable costs in catfish production, and between 2006 and 2012 feed prices increased >90% (Hanson and Sites 2014).

[1] Correspondence to: leighanne.bright@kysu.edu

Corn and soybeans are the primary ingredients in catfish feed, representing up to 32 and 42% of total feed ingredients, respectively (Robinson 1991). Distiller's dried grains with solubles (DDGS), a co-product of the ethanol industry, can be less expensive than either soybean meal (SBM) or corn on a per-unit protein basis (Zhou et al. 2010). In recent years, policies encouraging the production of fuel ethanol in the USA have stimulated a considerable increase in the production of DDGS (U.S. Grains Council 2015).

Until recently, the majority of the dry-grind ethanol plants produced a DDGS byproduct containing 26–34% protein (Rosentrater and Muthukumarappan 2006). However, many ethanol plants are implementing a modified dry milling process called fractionation to increase ethanol yields. In this new process, whole corn is milled, then sorted into separate fractions: corn germ, bran, and the endosperm (which is used for ethanol fermentation). The two main co-products of the modified process are corn germ and high-protein distiller's dried grains (HP-DDG). This HP-DDG product has a protein level of 41–43% and lower levels of fat and phosphorus than that in traditional DDGS because it does not contain the solubles component that would normally be added back to the distiller's dried grains.

The higher protein content of HP-DDG could make them even more attractive for inclusion in fish diets because protein is generally the most expensive nutrient component in aquafeeds. Traditionally, fishmeal (FM) has been the predominant protein source in most aquaculture diets, but high cost and reduced supply have caused fish nutritionists to evaluate less-expensive plant-based protein sources (Tidwell and Allan 2001; Finley and Fry 2009). Market prices of DDGS have been generally between 5 and 20% those of FM (ERS 2011). Because of biofuel production, it is estimated that in the next few years nearly 35 m.t./yr of HP-DDG will be available in the marketplace (RFA 2011). As a result, there is an increasing interest in using DDGS in aquaculture diets around the world because of its moderately high protein content, low phosphorus content, and low cost compared with those of FM.

Compared with other plant-based proteins, there are several positive attributes of DDGS, including a lack of antinutritional factors as found in SBM (trypsin inhibitors; Wilson and Poe 1985), rapeseed meal (glucosinolates and erucic acid; Jauncey and Ross 1982), and cottonseed meal (gossypol; Robinson 1991). In addition, DDGS contains low levels of phytate compared with other plant-based ingredients (Stein and Shurson 2009). Vitamins, including riboflavin, niacin, pantothenic acid, folic acid, and choline are much higher in DDGS than in corn (Hertrampf and Piedad-Pascual 2000). Another positive characteristic of DDGS is that it contains prebiotics such as β-glucan and mannans, which have been reported to stimulate fish immune responses because of the fermentation products that are retained (Lim et al. 2007).

Several studies referenced here have evaluated the original DDGS product as an ingredient in diets for channel catfish. Lovell (1989) reported that when used in combination with 10% FM, up to 30% DDGS can be used in channel catfish diets. Tidwell et al. (1990) and Webster et al. (1991) found that 40 and 35% DDGS, respectively, can be used in channel catfish diets as substitutes for SBM and corn meal (CM). A diet containing 70% DDGS appeared to be deficient in lysine (Webster et al. 1991). Webster et al. (1992) found that the weight gain of fish fed a diet with 0% FM, 35% DDGS, and 49% SBM was similar to that of fish fed a diet containing 12% FM and 48% SBM. Webster et al. (1993) also found that 30% DDGS can be used as a replacement of a mixture of SBM and CM in channel catfish diets containing 8% FM.

Because DDGS is a high-fiber, low-carbohydrate product, it is important to evaluate the impact of DDGS on feed pellet characteristics. For example, pellet durability, water stability, and floatability have been shown to decline when DDGS is increased in formulations (Ayadi et al. 2011a, 2011b). Physical properties of the pellets are also affected by processing conditions (e.g., processing temperatures, screw speeds, water addition, and steam addition). Because of the high fiber content of DDGS, proper grinding and extrusion processing conditions are necessary to produce high-quality feed pellets (Chevanan et al. 2008, 2010).

To summarize, experimental formulations containing 20–40% traditional DDGS have been successfully used in channel catfish diets and inclusion levels can be increased further with lysine supplementation. However, most of this work was conducted on DDGS from beverage distilleries; few have used corn-based DDGS from fuel ethanol manufacturing. Ironically, over 95% of all DDGS is now produced in fuel plants (RFA 2011). Beverage-based DDGS and fuel-based HP-DDG may differ. More importantly, many plants have installed fractionation systems and now produce a high-protein product (HP-DDG), which not only has higher protein content but also lower fiber and fat content

(RFA 2011). This study was designed to evaluate graded levels of HP-DDG on both the growth performance of channel catfish and the characteristics of the manufactured feed pellets.

Materials and Methods

Feed Blend Preparation

Four ingredient blends, each with a target protein content of 37% (dry basis), with progressively increasing contents of HP-DDG (0, 20, 40, and 40% with supplemental lysine) and progressively decreasing amounts of SBM, poultry byproduct meal, and corn (Table 1) were used to prepare nutritionally balanced diets for channel catfish. For each diet, all dry ingredients were individually ground with a pilot-scale hammermill (Model DAS 506, Fitzpatrick Co., Elmhurst, IL, USA) to a fine particle size (500 μm), then combined with the fish oil and mixed in a twin shell dry blender (Patterson-Kelley Co., Inc., East Stroudsburg, PA, USA) for 20 min to produce a homogeneous bulk.

Extrusion Processing

Extrusion of the diets was performed using a pilot-scale, co-rotating, fully intermeshing, self-wiping, twin-screw extruder (Wenger TX-52, Sabetha, KS, USA). The extruder had two 52-mm diameter screws and a barrel length of 1340 mm, with a 25.5:1 length-to-diameter ratio. The screw speed of the extruder could operate from 100 to 1800 rpm, and the barrel temperatures could be adjusted within a range of 60–150 C.

After the prepared blends were processed in the extruder, they were cooled for 72 h at room temperature (24 ± 1 C), dried in an oven (Model TAH-500, Grieve Corporation, Round Lake, IL, USA) for 24 h at 45 ± 0.5 C, then subjected to extensive physical property testing. Analyzed compositions of finished diets are presented in Table 2.

TABLE 1. *Ingredient formulations of four experimental diets containing varying percentages of high-protein distiller's grains (HP-DDG) fed to channel catfish.*

Ingredient	Diet: Control	20% HP-DDG	40% HP-DDG	40% HP-DDG + Lysine
HP-DDG[1]	0	20	40	40
Fishmeal[2]	2	2	0	0
Soybean meal[3]	57	44	33	33
Poultry byproduct meal	4	2	0	0
Corn	31.5	26.5	21.5	20.5
Lysine	0	0	0	1
Fish oil	3.5	3.5	3.5	3.5
Choline	0.3	0.3	0.3	0.3
Mineral mix	0.5	0.5	0.5	0.5
Vitamin mix	0.5	0.5	0.5	0.5
Dicalcium phosphate	0.7	0.7	0.7	0.7
Total	100	100	100	100

[1]High-protein distiller's dried grains, Poet Nutrition, Sioux Falls, SD, USA.

[2]Menhaden special select, Omega Protein, Inc., Houston, TX, USA.

[3]53% protein, solvent-extracted, Dakotaland Feeds, LLC, Huron, SD, USA.

TABLE 2. *Analyzed composition of four experimental diets containing varying percentages of high-protein distiller's grains as fed to channel catfish.*[1]

Analyzed Composition	Control	20% HP-DDG	40% HP-DDG	40% HP-DDG + Lysine
Crude protein	37.9 ± 0.3	37.2 ± 0.4	36.7 ± 0.6	37.3 ± 0.6
Crude fat	3.7 ± 0.1	3.2 ± 0.2	4.6 ± 0.2	4.6 ± 0.2
Crude fiber	2.9 ± 0.2	3.1 ± 0.3	4.0 ± 0.0	3.7 ± 0.0
Ash	6.4 ± 0.1	5.3 ± 0.1	4.3 ± 0.0	4.2 ± 0.1

HP-DDG = high-protein distiller's grains.

[1]Values are expressed as means (± SD) of three replicates per diet.

Physical Properties of Extruded Feeds

After drying and cooling, the finished pellets were analyzed for moisture content (% db), bulk density (kg/m^3), expansion ratio, and pellet durability index (PDI, %) (Table 3). All properties were determined using triplicate ($n = 3$) samples, except unit density, which was based on $n = 10$ replications.

Moisture content was determined following Method 44–19 (AACC 2000), by drying at 135 C for 2 h using a forced-convection oven (Precision, Thermo Electron Corp., Waltham, MA, USA). Bulk density was determined as the ratio of the mass of extrudates that could fill a given bulk container (1 L) and was measured using a standard bushel tester (Seedburo Equipment Company, Chicago, IL, USA), following the method recommended by USDA (2009).

TABLE 3. *Characteristics of finished pellets of four experimental diets containing varying percentages of high-protein distiller's grains (HP-DDG) as fed to channel catfish.*[1,2]

Characteristics	Control	20% HP-DDG	40% HP-DDG	40% HP-DDG + Lysine
Moisture (%)	8.3 ± 0.1^{a}	8.2 ± 0.3^{a}	7.2 ± 0.2^{b}	6.7 ± 0.4^{b}
Unit density (kg/m^3)	468.1 ± 25.7^{c}	583.7 ± 43.0^{b}	620.9 ± 6.0^{ab}	659.2 ± 19.8^{a}
Expansion ratio[a]	3.0 ± 0.1^{a}	2.4 ± 0.1^{b}	2.3 ± 0.0^{c}	2.2 ± 0.0^{d}
Pellet durability index (%)[3]	91.5 ± 0.0^{c}	92.4 ± 0.1^{b}	93.7 ± 0.3^{a}	92.7 ± 0.2^{ab}

[1]Values are expressed as means (± SD) of three replicates per diet.
[2]Different letters indicate significant differences ($P \geq 0.05$) among diets for a given measured trait.
[3]The diameter of the final pellet (cm) divided by the diameter of the die nozzle.

PDI was determined according to Method S269.4 (ASAE 2004). Approximately 100 g of extrudate sample from each blend was manually sieved (4.0 mm, No. 5, USA standard testing sieve, ASTM E-11 specification, Daigger, Vernon Hills, IL, USA) for 10 sec and then tumbled in a pellet durability tester (Model PDT-110, Seedburo Equipment Company, Chicago, IL, USA) for 10 min. Afterward, the samples were again manually sieved for 10 sec and weighed on an electronic balance (Explorer Pro, Model EP4102, Ohaus, Pine Brook, NJ, USA). Relating the extrudate sample weights before and after tumbling, the PDI (%) was calculated as: $PDI = \left(\frac{Ma}{Mb}\right) \times 100$ where M_a was the mass (g) after tumbling and M_b was the sample mass (g) before tumbling.

Fish and Experimental System

Juvenile channel catfish were donated by Pete Pfeiffer Fish and Wildlife Hatchery, Kentucky. After being graded to a similar size (7.1 ± 2.3 g), five fish were retained to be analyzed for baseline whole-body proximate analysis, and the remaining fish were randomly stocked into twelve 260-L polyethylene tanks at 25 fish per tank. All fish were fed the control diet (0% HP-DDG) for 1 wk while being acclimated to the system, then switched to the experimental diets. There were three replicate tanks per experimental diet. Fish were fed one of the four diets to apparent satiation twice daily (0800 and 1600 h) for 9 wk. Fish were continuously monitored while feeding and if any pellets were uneaten, they remained in the tank. The amount of diet fed to fish in each tank was recorded at the end of each week.

Water Quality

Tanks were in a shared recirculating system. Dissolved oxygen and temperature were monitored twice daily with a dissolved oxygen meter (Model 85, YSI, Inc., Yellow Springs, OH, USA). Levels of total ammonia–nitrogen (TAN), nitrite–nitrogen, and pH were monitored thrice per week with a spectrophotometer (Model Odyssey DRT 2500, HACH Company, Loveland, CO, USA). Alkalinity and hardness were monitored thrice per week by titration (HACH digital titrator). Over the duration of the study, water quality measurements averaged 29.1 ± 0.6 C for water temperature, 59.0 ± 19.8 mg/L total alkalinity, 212 ± 12 mg/L of water hardness, 0.23 ± 0.13 mg/L for TAN, 0.01 ± 0.01 mg/L for unionized ammonia, 0.82 ± 0.59 mg/L for nitrite–nitrogen, and 7.5 ± 0.3 for pH.

Harvest

After 9 wk, all fish from each tank were harvested, bulk weighed, counted, and then individually weighed and measured (total length). Six fish from each tank were randomly selected, anesthetized with quinaldine sulfonate (Sure-Life Laboratories, Inc., Seguin, TX, USA; tranquil), individually homogenized, and submitted for either whole-body proximate analysis (three fish) or stored under liquid nitrogen for fatty acid and amino acid analyses (three fish)

TABLE 4. *Amino acid profile (as a % of diet) of four experimental diets containing varying levels of high-protein distiller's grains (HP-DDG).*[1]

	Diet			
Amino acid	Control	20% HP-DDG	40% HP-DDG	40% HP-DDG + Lysine
Essential amino acid				
Arg	2.36 ± 0.08	2.25 ± 0.16	1.78 ± 0.05	1.86 ± 0.02
His	0.91 ± 0.08	0.93 ± 0.07	0.91 ± 0.08	0.96 ± 0.05
Ile	1.55 ± 0.05	1.54 ± 0.01	1.45 ± 0.04	1.50 ± 0.01
Leu	2.76 ± 0.06	3.04 ± 0.38	3.62 ± 0.07	3.79 ± 0.07
Lys	2.14 ± 0.08	2.00 ± 0.16	1.53 ± 0.05	2.41 ± 0.02
Met	0.52 ± 0.00	0.54 ± 0.16	0.55 ± 0.00	0.56 ± 0.00
Phe	1.67 ± 0.05	1.70 ± 0.05	1.69 ± 0.04	1.77 ± 0.03
Thr	1.27 ± 0.01	1.27 ± 0.00	1.22 ± 0.01	1.29 ± 0.05
Trp	0.45 ± 0.01	0.42 ± 0.06	0.35 ± 0.01	0.32 ± 0.04
Val	1.73 ± 0.04	1.73 ± 0.02	1.70 ± 0.03	1.76 ± 0.02
Nonessential amino acid				
Ala	1.71 ± 0.04	1.82 ± 0.11	2.03 ± 0.03	2.14 ± 0.12
Asp	3.56 ± 0.04	3.41 ± 0.30	2.83 ± 0.04	2.96 ± 0.14
Cys	0.45 ± 0.00	0.47 ± 0.01	0.51 ± 0.03	0.54 ± 0.06
Glu	5.74 ± 0.07	5.76 ± 0.11	5.63 ± 0.04	5.86 ± 0.05
Gly	1.68 ± 0.01	1.59 ± 0.13	1.26 ± 0.01	1.31 ± 0.04
Pro	1.88 ± 0.10	2.03 ± 0.33	2.33 ± 0.16	2.43 ± 0.06
Ser	1.30 ± 0.01	1.33 ± 0.06	1.34 ± 0.01	1.41 ± 0.02
Tyr	1.11 ± 0.07	1.17 ± 0.06	1.16 ± 0.04	1.22 ± 0.07

[1] Values are expressed as means (± SD) of three replicates per diet.

by a commercial laboratory (Eurofins Scientific, Inc., Des Moines, IA, USA) (Tables 4 and 5).

Calculations and Definitions

Growth performance parameters were calculated with the following equations. Feed conversion ratio (FCR) was calculated as dry feed intake (g) divided by total wet weight gain (g). Condition factor (K) was calculated as $100 \times W/L^3$, where W is weight (g) and L is total length (cm). Average harvest weight was calculated as total weight gain (g) divided by number of fish. Weight gain (%) was calculated as [(final average weight (g) – initial weight (g))/initial weight] × 100. The term polyunsaturated fatty acid (PUFA) was used to designate all fatty acids with two double bonds or more, and highly unsaturated fatty acid was used to designate a subsample of PUFA with 20 or more carbons, as described by Brett and Muller-Navarra (1997).

Statistical Analyses

Data were analyzed using SAS software (SAS Institute, Cary, NC, USA) or Statistix analytical software (Tallahassee, FL, USA), using a type I error rate of 0.05 by ANOVA. If significant differences were identified, the least significant difference test was used to identify differences among treatments (Steel and Torrie 1980). All percentage and ratio data were transformed to arcsine values before analysis (Zar 1984). Untransformed data are presented to facilitate interpretation.

Results and Discussion

After feeding the four diets for 9 wk, there was no significant difference ($P \geq 0.05$) in survival among fish fed the four diets (Table 6), which averaged 99.7% overall. Weight gain was significantly greater in fish fed the 20% HP-DDG diet than in fish fed 40% HP-DDG or 40% + lysine. The fish fed the control diet were intermediate between fish fed the 20% HP-DDG diet and those fed the 40% + lysine diet. There was no significant difference in FCR or K among fish fed the four diets. Because adding lysine to the 40% HP-DDG diet restored fish performance to fish fed the control diet, the 40% HP-DDG diet was likely limiting in lysine.

TABLE 5. *Fatty acid composition (percentage of total fatty acids) of four experimental diets containing varying levels of high-protein distiller's grains (HP-DDG) as fed to channel catfish.*[1]

Fatty acid	Control	20% HP-DDG	40% HP-DDG	40% HP-DDG + Lysine
14:0	3.2 ± 0.1	2.9 ± 0.0	2.5 ± 0.1	2.2 ± 0.0
16:0	12.3 ± 0.4	9.9 ± 0.1	9.5 ± 0.0	8.6 ± 0.3
16:1 (n-7)	4.7 ± 0.3	4.0 ± 0.1	3.5 ± 0.0	3.1 ± 0.2
18:0	3.0 ± 0.2	1.9 ± 0.0	1.7 ± 0.0	1.5 ± 0.1
18:1(n-9)	13.9 ± 0.2	10.3 ± 0.0	10.5 ± 0.1	9.2 ± 0.20
18:2 (n-6)	21.1 ± 1.2	15.6 ± 0.5	16.9 ± 1.1	15.1 ± 0.4
18:3 (n-3)	3.1 ± 0.2	1.6 ± 0.1	1.5 ± 0.2	1.1 ± 0.1
20:4 (n-6)	1.3 ± 0.2	1.1 ± 0.1	0.9 ± 0.1	0.9 ± 0.2
20:5 (n-3)	5.2 ± 0.1	4.6 ± 0.1	3.9 ± 0.4	3.4 ± 0.2
22:5 (n-3)	0.9 ± 0.3	0.9 ± 0.1	0.8 ± 0.0	0.6 ± 0.2
22:6 (n-3)	3.4 ± 0.6	3.3 ± 0.3	2.7 ± 0.4	2.5 ± 0.3
Other				
Saturates	20.2 ± 1.1	6.2 ± 0.1	14.9 ± 0.1	13.5 ± 0.1
Monenes	20.1 ± 0.04	15.6 ± 0.6	15.4 ± 0.1	13.6 ± 0.5
Dinenes	21.3 ± 1.2	15.8 ± 0.4	17.0 ± 1.1	15.3 ± 0.4
PUFA[1]	36.6 ± 1.1	28.2 ± 1.3	27.9 ± 1.9	24.4 ± 1.8
HUFA[1]	11.1 ± 0.5	10.2 ± 1.2	8.4 ± 0.8	7.5 ± 1.1
n-3	12.6 ± 0.6	10.3 ± 0.7	9.0 ± 0.1	7.8 ± 0.6
n-6	22.3 ± 1.0	16.7 ± 0.6	17.8 ± 1.0	15.9 ± 0.5
n-3/n-6	0.6 ± 0.0	0.6 ± 0.0	0.5 ± 0.0	0.5 ± 0.0

PUFA = polyunsaturated fatty acid; HUFA = highly unsaturated fatty acid.
[1] Values are expressed as means (± SD) of three replicates per diet.

TABLE 6. *Means (±SE) of average harvest weight (AHW), survival, feed conversion ratio (FCR), condition factor (K), and percent weight gain (wt gain %) of channel catfish fed four experimental diets containing varying levels of high-protein distiller's grains (HP-DDG).*[1]

	Diet			
	Control	20% HP-DDG	40% HP-DDG	40% HP-DDG + Lysine
AHW (g)	7.7 ± 6.2^{ab}	86.8 ± 10.9^{a}	57.0 ± 4.4^{c}	73.7 ± 4.9^{b}
Survival (%)	98.6 ± 2.3^{a}	100.0 ± 0.0^{a}	100.0 ± 0.0^{a}	100.0 ± 0.0^{a}
FCR	1.1 ± 0.1^{a}	1.1 ± 0.3^{a}	1.2 ± 0.0^{a}	1.1 ± 0.0^{a}
K	1.1 ± 0.0^{a}	1.1 ± 0.0^{a}	0.9 ± 0.0^{a}	1.0 ± 0.0^{a}
% Wt gain	988.2 ± 111.3^{a}	1149.1 ± 176.1^{a}	718.2 ± 49.1^{b}	959.2 ± 52.5^{a}

[1] Significant differences ($P \leq 0.05$) are indicated by different superscript letters within rows.

The results of this study are largely in agreement with previous studies using traditional DDGS from beverage-based distillation. Lim et al. (2009) suggested that with lysine supplementation, 40% DDGS could be included in diets for channel catfish, without affecting growth performance, utilization efficiency, or survival. In a pond study, Robinson and Li (2008) also showed that fish fed 40% DDGS with supplemental lysine performed similar to those fed a control diet. Tidwell et al. (1990) reported that in diets containing 8% FM, 40% DDGS could be used in channel catfish diets without lysine supplementation. In this study, the 40% HP-DDG diets contained no FM. The best-performing diet contained not only 20% HP-DDG, but also contained small amounts of FM (2%) and poultry byproduct meal (2%) as did the control diet (2% and 4%, respectively). Webster et al. (1992) found that the weight gain of channel catfish fed a diet with 0% FM, 35% DDGS, 49% SBM, and lysine supplementation was similar to that of a diet with 12% FM and 48% SBM.

Whole-body proximate compositions were affected by dietary treatment (Table 7). Protein

TABLE 7. *Analyzed composition (mean ± SD) of whole bodies from fish fed four experimental diets containing varying levels of high-protein distiller's grains (HP-DDG).*[1]

Proximate variable	Diet			
	Control	20% HP-DDG	40% HP-DDG	40% HP-DDG + Lysine
Moisture (%)	71.0 ± 0.1^{a}	69.1 ± 1.0^{a}	70.0 ± 0.6^{a}	68.6 ± 0.3^{a}
Protein (%)	13.9 ± 0.1^{a}	13.6 ± 0.1^{ab}	13.2 ± 0.1^{b}	13.4 ± 0.2^{b}
Lipid (%)	10.9 ± 0.1^{a}	11.7 ± 0.4^{a}	11.8 ± 0.1^{a}	12.0 ± 0.3^{a}
Ash (%)	3.0 ± 0.2^{a}	2.6 ± 0.3^{ab}	1.9 ± 0.1^{bc}	1.7 ± 0.1^{c}

[1]Significant differences ($P \leq 0.05$) are indicated by different superscript letters within rows.

concentration was significantly higher in fish fed the control diet than in fish fed the 40% HP-DDG or 40% HP-DDG + lysine diets. Fish fed the 20% HP-DDG diet were intermediate in protein concentration and not significantly different from those fed other diets. There was no significant difference in whole-body lipid or moisture concentrations among fish fed any of the four diets. Fish fed the 0% HP-DDG control diet had significantly higher whole-body ash concentrations than fish fed the 40% HP-DDG or 40% HP-DDG + lysine diets, but not significantly different from fish fed the 20% HP-DDG diet, which had a significantly higher ash concentration than fish fed the 40% HP-DDG + lysine diet.

Lim et al. (2009) reported higher whole-body fat content in channel catfish fed diets containing 40% DDGS compared with those fed a control diet, even though the diets were isocaloric and contained approximately the same lipid levels. Robinson and Li (2008) also reported greater levels of fillet fat in channel catfish fed diets containing DDGS compared with those fed a control diet, which was suggested to be due to the higher energy content of the DDGS diets as their diets were not adjusted to be isocaloric. In this study, there were no differences in whole-body lipid levels between fish fed the experimental diets, even though the lipid levels of both 40% HP-DDG diets (with and without lysine) were greater than the control diet and the 20% HP-DDG diet. Additionally, the whole-body protein levels of channel catfish fed both 40% HP-DDG diets were less than in fish fed the control diet, although the protein levels of experimental diets were similar.

Analysis of the physical characteristics of experimental diets can be particularly important when investigating new feed ingredients such as HP-DDG. Compared with traditional DDGS, the HP-DDG contains more protein (41.3%), less lipid (3.7%), and more fiber (25.2%) than traditional DDGS (27, 9.0, and 9.1%, respectively; Webster et al. 2008). The relatively high fiber content of HP-DDG is evident in the proximate composition of the finished diets, in which relative to the control diet there was a 19% increase in fiber in the 20% HP-DDG and a 41% increase in the 40% HP-DDG diet. The relatively high fiber content of HP-DDG may limit inclusion rates at some level because of manufacturing difficulties during extrusion. Moisture content of the finished feeds were significantly higher ($P \leq 0.05$) in the control and 20% HP-DDG feeds (Table 3) compared with the 40% HP-DDG and the 40% HP-DDG + lysine diets, which were not significantly different ($P > 0.05$).

As these are extruded pellets, pellet expansion and pellet durability are important characteristics. The expansion ratio was significantly different among all four diets ($P \leq 0.05$), being highest in the control diet and decreasing as inclusion level of HP-DDG increased. The unit density of the control diet was significantly lower ($P \leq 0.05$) than all other diets, indicating less weight per unit of volume. The unit density tended to increase as HP-DDG increased and reflected the decreasing expansion ratio. PDI measures the ability of finished feed pellets to stand up to handling and shipping. The PDI of the control diet was significantly lower ($P \leq 0.05$) than other diets and tended to increase as inclusion level of HP-DDG increased. This is somewhat surprising based on the high fiber content of the HP-DDG. However, it might be explained in terms of the lower expansion of the diets containing HP-DDG and the resulting higher density of those pellets better resisting handling than the low-density pellets of the control diets. The relatively high lipid and fiber content of the HP-DDG has the potential to negatively impact the expansion and stability of the extruded pellets. High lipid content can "lubricate" the extruder barrel and reduce the compression and pressure within the barrel. This can negatively impact pellet expansion as measured by expansion ratio and unit density. As the percentage of HP-DDG increased, expansion ratio decreased and unit density increased. The increasing inclusion levels of the HP-DDG were reflected in higher fiber content in the finished feeds. However, rather than reducing pellet stability (as measured by the PDI), it was actually higher in the two diets containing 40% HP-DDG.

These data indicate that HP-DDG appears to be a suitable ingredient in channel catfish diets up to at least 20% of total formulation. Because added lysine restored performance to control level, the 40% HP-DDG diet was likely limiting in lysine. The inclusion of HP-DDG did reduce pellet expansion by improved pellet durability.

Acknowledgments

We thank Kyle Schneider who assisted with system maintenance. This research was performed at KSU Experiment Station number KYSU-000046. This research was funded by a USDA/CREES grant to Kentucky State University under agreement KYX-80-9104A. Additional support was provided by Kentucky's Regional University Trust Fund to the Aquaculture Program as KSU's Program of Distinction.

Literature Cited

AACC (American Association of Cereal Chemists). 2000. Method 44–19, moisture – air oven method, drying at 135 °C. AACC approved methods, 10th edition. AACC, St. Paul, Minnesota, USA.

ASAE (American Society of Agricultural and Biological Engineers). 2004. Engineering standards: practices and data. ASAE, St. Joseph, Michigan, USA.

Ayadi, F., K. Muthukumarappan, K. A. Rosentrater, and M. L. Brown. 2011a. Single screw extrusion processing of distillers dried grains with solubles (DDGS)-based yellow perch (*Perca flavenscens*) feeds. Cereal Chemistry 88(2):179–188.

Ayadi, F., K. A. Rosentrater, K. Muthukumarappan, and M. L. Brown. 2011b. Twin screw extrusion processing of distillers dried grains with solubles (DDGS)-based rainbow trout (*Onchorhynchus mykiss*) feeds. Cereal Chemistry 88(4):363–374.

Brett, M. and D. Muller-Navarra. 1997. The role of highly unsaturated fatty acids in aquatic foodweb processes. Freshwater Biology 38(3):483–499.

Chevanan, N., K. A. Rosentrater, and K. Muthukumarappan. 2008. Effect of DDGS, moisture content, and screw speed on the physical properties of extrudates in single screw extrusion. Cereal Chemistry 85(2):132–139.

Chevanan, N., K. A. Rosentrater, and K. Muthukumarappan. 2010. Effects of processing conditions on single screw extrusion of feed ingredients containing DDGS. Food and Bioprocess Technology 3(1):111–120.

ERS (Economic Research Service). 2011. Feed grains database: yearbook tables. ERS, U.S. Department of Agriculture, Washington, District of Columbia, USA. http://www.ers.usda.gov/data-products/feed-grains-database.aspx.

Finley, W. and J. Fry. 2009. Expanding opportunities for vegetable proteins in aquaculture feeds. World Aquaculture 40(2):29–32.

Hanson, T. and D. Sites. 2014. 2013 U.S. catfish database. Fisheries and Allied Aquaculture Department, Series No. 1, Auburn, Alabama, USA.

Hertrampf, J. W. and F. Piedad-Pascual. 2000. Distillery by-products. Pages 115–124 *in* J. W. Hertrampf and F. Piedad-Pascual, editors. Handbook on ingredients for aquaculture feeds. Kluwer Academic Publishers, Dordrecht, Netherlands.

Jauncey, K. and B. Ross. 1982. A guide to tilapia feeds and feeding. Institute of Aquaculture, University of Sterling, Scotland.

Lim, C., J. C. Garcia, M. Yildirim-Aksoy, P. H. Klesiu, C. A. Shoemaker, and J. J. Evans. 2007. Growth response and resistance to *Streptococcus iniae* of Nile tilapia, *Oreochromis niloticus*, fed diets containing distiller's dried grains with solubles. Journal of the World Aquaculture Society 38(2):231–237.

Lim, C., M. Yildirim-Aksoy, and P. H. Klesius. 2009. Growth response and resistance to *Edwardsiella ictaluri* of channel catfish, *Ictalurus punctatus*, fed diets containing distiller's dried grains with solubles. Journal of the World Aquaculture Society 40(2):182–193.

Lovell, T. 1989. Nutrition and feeding of fish. Van Nostrand Reinhold, New York, New York, USA.

NMFS (National Marine Fisheries Service). 2015. http://www.nmfs.noaa.gov/aquaculture/aquaculture_in_us.htm

RFA (Renewable Fuels Association). 2011. Annual industry outlook. RFA, Washington, District of

Columbia, USA. http://www.ethanolrfa.org/resources/publications/outlook/.

Robinson, E. H. 1991. Improvement of cottonseed meal protein with supplemental lysine in feeds for channel catfish. Journal of Applied Aquaculture 1(2):1–14.

Robinson, E. H. and M. H. Li. 2008. Replacement of soybean meal in channel catfish, *Ictalurus punctatus*, diets with cottonseed meal and distiller's dried grains with solubles. Journal of the World Aquaculture Society 39(4):521–527.

Rosentrater, K. A. and K. Muthukumarappan. 2006. Corn ethanol coproducts: generation, properties, and future prospects. International Sugar Journal 108:648–657.

Steel, R. G. D. and J. H. Torrie. 1980. Principles and procedures of statistics, a biometrical approach, 2nd edition. McGraw-Hill, New York, New York, USA.

Stein, H. H. and G. C. Shurson. 2009. The use and application of distillers dried grains with solubles in swine diets. Journal of Animal Sciences 87(4):1292–1303.

Tidwell, J. H. and G. L. Allan. 2001. Fish as food: aquaculture's contribution. EMBO Reports 2(11):958–963.

Tidwell, J. H., C. D. Webster, and D. H. Yancey. 1990. Evaluation of distillers' grains with solubles in prepared channel catfish diets. Transactions of the Kentucky Academy of Science 51(3–4):135–138.

U.S. Grains Council. 2015. Buying and selling DDGS. . www.grains.org/buyingselling/ddgs.

USDA (U.S. Department of Agriculture). 2009. Practical procedures for grain handlers: inspecting grain. Grain Inspection, Packers, and Stockyards Administration, USDA, Washington, District of Columbia, USA. http://www.gipsa.usda.gov/fgis/publication/ref/primer.pdf.

Webster, C. D., J. H. Tidwell, and D. H. Yancey. 1991. Evaluation of distillers' grains with solubles as a protein source in diets for channel catfish. Aquaculture 96(2):179–190.

Webster, C. D., J. H. Tidwell, L. S. Goodgame, D. H. Yancey, and L. Mackey. 1992. Use of soybean meal and distillers grains with solubles as partial or total replacement of fish meal in diets for channel catfish, *Ictalurus punctatus*. Aquaculture 106(3–4):301–309.

Webster, C. D., J. H. Tidwell, and L. S. Goodgame. 1993. Growth, body composition and organoleptic evaluation of channel catfish fed diets containing different percentages of distillers' grains with solubles. The Progressive Fish Culturist 55(2):95–100.

Webster, C. D., K. R. Thompson, L. S. Metts, and L. A. Muzinic. 2008. Use of distiller's grains with solubles and brewery by-products in fish and crustacean diets. Pages 475–499 *in* C. E. Lim, C. D. Webster, and C.-S. Lee, editors. Alternative protein sources in aquaculture diets. Haworth Press, New York, New York, USA.

Wilson, R. P. and W. E. Poe. 1985. Relationship of whole body and egg essential amino acid patterns to amino acid requirement patterns in channel catfish, *Ictalurus punctatus*. Comparative Biochemistry and Physiology Part B: Comparative Biochemistry 80(2):385–388.

Zar, J. H. 1984. Biostatistical analysis. Prentice Hall, Englewood Cliffs, New Jersey, USA.

Zhou, P., W. Zhang, D. A. Davis, and C. Lim. 2010. Growth response and feed utilization of juvenile hybrid catfish fed diets containing distiller's grains with solubles to replace a combination of soybean meal and corn meal. North American Journal of Aquaculture 72:298–303.