Single-Screw Extrusion Processing of Distillers Dried Grains with Solubles (DDGS)-Based Yellow Perch (*Perca flavescens*) Feeds

Ferouz Y. Ayadi,[1] Kasiviswanathan Muthukumarappan,[1] Kurt A. Rosentrater,[2,3] and Michael L. Brown[4]

ABSTRACT

Cereal Chem. 88(2):179–188

This study was conducted to investigate the production of balanced diets for juvenile yellow perch (*Perca flavescens*) feeds. Six isocaloric (≈3.21 kcal/g), isonitrogenous (30.1 ± 0.4% db) ingredient blends were formulated with 0, 10, 20, 30, 40, and 50% distillers dried grains with solubles (DDGS), and appropriate amounts of soybean meal, fish meal, vitamins, and minerals. Extrusion cooking was performed using a laboratory-scale single-screw extruder at a constant barrel temperature profile of 40–90–100°C, and a constant screw speed of 230 rpm (24.1 rad/sec). The mass flow rate was determined during processing; it generally increased with progressively higher DDGS content. Additionally, moisture content, water activity, unit density, expansion ratio, compressive strength, compressive modulus, pellet durability index, water stability, and color were extensively analyzed to quantify the effects of DDGS content on the physical properties of the resulting extrudates. Significant differences ($P < 0.05$) between blends were observed for color and water activity for both the raw material and extrudates, respectively, and for the unit density of the extrudates. There were significant changes in brightness (L), redness (a), and yellowness (b) among the final products when increasing the DDGS content of the blends. Expansion ratio and compressive strength of the extrudates were low. On the other hand, all blends showed high pellet durability (PDI ≥ 96.18%). Overall, it was ascertained that DDGS could be successfully included at rates of <50%, and that each of the ingredient blends resulted in viable, high quality extrudates.

Aquaculture is one of the fastest growing sectors in the food producing industries. It increased from a per capita supply of 0.7 kg in 1970 to 7.8 kg in 2006. With an annual growth rate of 6.9%, it exceeded by far the annual growth rate of the world's population, which has risen from 3.7 billion in 1970 to 6.6 billion in 2006, and reached a peak growth rate of 2%/year during 1965-1970 (FAO 2009: ftp.fao.org/docrep/fao/011/i0250e/i0250e.pdf) (PRB 2008: prb.org/ pdf06/06WorldDataSheet.pdf) (UN 2007: http://www.un.org/esa/population/publications/wpp2006/WPP2006_Highlights_rev. pdf.). Comparing aquaculture production in the early 1950s to that in 2006, it grew from 1 million tonnes per year to over 51 million tonnes, with a value of over 78 billion US dollars. The world's increasing demands for seafood also results in increasing needs for fish feed. Commonly, high amounts of fish meal are used in these diets to provide fish with proteins that are essential for their metabolism and growth. Fish meal has become a highly questioned commodity in recent years, due to high cost and declining supplies. Investigators have begun looking for alternative protein sources. Much research has been pursued to find reasonable, cost efficient, and compatible alternatives. For example, Goda et al (2007) found that equivalent effects on growth rate and feed utilization could be achieved by totally replacing fish meal with poultry by-product meals (PBM) in diets for African catfish. However, the composition and quality of PBM varies because it is initially a waste product. Accordingly, in similar trials, where PBM was used as the exclusive protein source in feeding humpback grouper, Shapawi et al (2007) observed a lower growth rate compared to fish meal, which might have been due to an insufficient amino acid balance in the PBM.

Bacterial protein meal (BPM) is another potential feed ingredient. BPM had been able to replace high-quality fish meal up to 25% in diets for juvenile fresh water Atlantic salmon (Storebakken et al 2004), and of levels ≤25–27% for rainbow trout (Aas et al 2006; Øverland et al 2006). Compared to fish meal, BPM contains lower lysine but higher concentrations of tryptophan; hence, a combination with fish meal or other protein sources is required to achieve a balance (Storebakken et al 2004). Other undesirable side effects have been reported regarding reduced digestibility of nitrogen, lipid, and energy when increasing the level of BPM compared to fish meal (Aas et al 2006).

A special focus of research in recent years has been on plant protein sources, which are mostly inexpensive in price, easy to obtain, and have relatively consistent composition compared to meat or poultry by-products (Davies and Arbold 2000; Samocha et al 2004). For example, partial replacement trials have been conducted using cottonseed meal, peanut leaf meal, corn gluten meal, pea protein concentrate, alfalfa, and many other plant materials (Ali et al 2003; Garduño-Lugo and Olvera-Novoa 2008; Guimarães et al 2008; Øverland et al 2009).

Because of its high protein content, stability on the market, and relatively low price, soybean meal (SBM) has become one of the most widely used fish meal substitutes in fish feed (Thompson et al 2008). Webster et al (1992) ascertained that optimal growth of blue catfish could be achieved for a diet including 48% SBM by the supplementation of 13% fish meal. In earlier studies, Wilson and Poe (1985) observed that growth and protein efficiency ratios of fingerling channel catfish were reduced by raw and improperly heated soybean meal. These ratios could only be enhanced by reducing the trypsin inhibitor activity (Wilson et al 1985), one of the primary antinutritional factors in soybean meal (Francis et al 2001). A total replacement of fish meal by soybean meal is only possible for preprocessed (Arndt et al 1999) and amino acid supplemented SBM blends to ensure feed efficiency, palatability, digestibility, and optimal growth (Viola et al 1981; Floreto et al 2000; El-Saidy and Gaber 2002).

Another alternative for fish meal may be distillers dried grains with solubles (DDGS), the residual leftover of corn kernel fermentation during fuel ethanol manufacturing. The ethanol industry has been growing rapidly due to changes in energy policies (RFA 2009: http://www.ethanolrfa.org/pages/statistics) (Voca et al 2009), therefore increasing amounts of DDGS have become available.

*The ***e*-X**tra logo stands for "electronic extra" and indicates that Figs. 1 and 2 appear in color online.

[1] South Dakota State University, Agricultural & Biosystems Engineering, Brookings, SD 57007.
[2] USDA-ARS, North Central Agricultural Research Laboratory, 2923 Medary Ave., Brookings, SD 57006.
[3] Corresponding author. Phone: 605-693-3241. Fax: 605-693-5240. E-mail: krosentr@ngirl.ars.usda.gov
[4] South Dakota State University, Wildlife & Fisheries Sciences, Brookings, SD 57007.

doi:10.1094/CCHEM-08-10-0118

The U.S. production of distillers grains has risen from 2.3 million tonnes in 1999 to 30.5 million tonnes in 2009 (RFA 2009: http://www.ethanolrfa.org/pages/industry-resources-coproducts).

For over a century now, DDGS has been fed to ruminant animals (USDA GIPSA 2006: http://archive.gipsa.usda.gov/advcommittee/ethanol_paper.pdf). In contrast to corn, DDGS contains approximately three times the amount of nutrients such as fat, protein, fiber, and minerals resulting from the fermentation process (Jacques et al 2003). In addition, DDGS contains no antinutritional factors compared to SBM (U.S. Grains Council 2008: http://www.grains.org/images/stories/DDGS_user_handbook/DDGS%20Handbook%20FULL.pdf). Preceding research with DDGS, which usually contains 27–33% protein and 5–12% crude fiber (Rosentrater and Muthukumarappan 2006) as a partial replacement for fish meal, showed effective and economical growth for tilapia (Coyle et al 2004) and for channel catfish (Webster et al 1991). Cheng and Hardy (2004) determined that DDGS could replace ≤50% of fish meal in fish feed for rainbow trout and then improved the substitution ≤75% by adding supplemental lysine and methionine. Furthermore, successful trials have been conducted with both partial and total replacement of fish meal by combinations of DDGS and SBM for freshwater prawn (Tidwell et al 1993).

Yellow perch (*Perca flavescens*) is a small-sized, low-fat fish in growing demand, especially near the Great Lakes area of the U.S. (González et al 2006). Diet formulations that are generally recommended have been based upon the requirements for trout and salmon, which often contain a minimum of 36% crude protein (Brown et al 1996). This occurred because there have only been a few nutritional studies undertaken for yellow perch. Ramseyer and Garling (1998) determined that protein levels of 210–270 g/kg of dry diet, with appropriate contents of amino acids and carbohydrates, should be suitable for yellow perch instead of higher and commonly used amounts of 400 g/kg of dry diet. So far, research for alternative protein sources in diets for yellow perch has only been performed by Kasper et al (2007), who concluded that yellow perch were able to effectively utilize diets containing solvent-extracted, dehulled, expelled or extruded soybean meal, with a conservative protein recommendation of 300 g/kg of diet. Fish meal protein was successfully replaced in their feeds.

Some studies have been conducted on processing DDGS-based tilapia feeds. In previous studies, Chevanan et al (2007a,b,c, 2008, 2009, 2010), Rosentrater et al (2009a,b), and Kannadhason et al (2009a,b, 2010) investigated how die dimensions, screw speeds, and barrel temperatures of the extruder, and ingredient moisture and DDGS content of various tilapia feed blends affected the resulting extrudate physical properties and extrusion processing parameters from both the single-screw and twin-screw extruders. Chevanan et al (2008) showed that ingredient moisture content and screw speed had significant effects on extrudate durability, color, and extruder throughput; DDGS could be included at ≤40% in the blend and still produced viable extrudates. In twin-screw studies, Chevanan et al (2007b) achieved viable pellets at DDGS inclusion levels at ≤60%; as DDGS increased, the extrudates exhibited higher moisture content, unit density, fiber, and fat content but decreased durability and expansion ratio. To date, however, no trials of partial or complete fish meal replacement using DDGS for yellow perch feeds have been conducted.

Industrial-scale extrusion cooking of animal feeds began between 1955 and 1960 (Moscicki and van Zuilichem 1983) and is commonly applied in commercial processing of aquafeeds to produce cost-effective, floating feeds (Tudor 1996; Opstvedt et al 2003). Extrusion is performed at high temperatures, for short residence times, with high pressures and high shear forces. Extrusion results in modifying and texturizing the food ingredients. Additionally, it can inactivate several antinutritional factors such as oxidative and other deterioration enzymes (Cheftel 1986). More information about extrusion processing can be found in Mercier et al (1989), Chang and Wang (1998), Riaz (2000), and other literary sources.

The objectives of this study were 1) to produce feed pellets for juvenile yellow perch (*Perca flavescens*) using DDGS as an alternative protein source, and 2) to examine the effects of varying DDGS content on the resulting physical properties of extrudates and on extruder processing parameters.

TABLE I
Ingredient Components (% db) and Nutrient Compositions (% db) of the Feed Blends[a]

Ingredients	Dry Weight of Ingredients (% db) in Diets 1	2	3	4	5	6
DDGS	0	10	20	30	40	50
Soybean meal	31.5	26	20.5	15	9.5	4
Fish meal (menhaden)	24	24	24	24	24	24
Vitamin mix	3	3	3	3	3	3
Mineral mix	8	8	8	8	8	8
Soybean oil	5.5	4.4	3.3	2.2	1.1	0
Celufil	17	13.6	10.2	6.8	3.4	0
CMC	5	5	5	5	5	5
Menhaden oil	6	6	6	6	6	6
Total	100.0	100.0	100.0	100.0	100.0	100.0
	Feed Blend Composition (% db)					
Total moisture (% wb)	19.5	18.7	18.2	18.4	19.1	18.6
Total dry matter (% wb)	80.5	81.3	81.8	81.6	80.9	81.4
Crude protein (% db)	29.5	29.6	30.4	30.4	30.2	30.3
Crude fat (% db)	16.0	16.6	16.4	16.4	16.7	18.1

[a] All blends were formulated on a dry basis, db.

MATERIALS AND METHODS

Feed Blend Preparation

Six isocaloric (≈3.21 kcal/g) ingredient blends (Table I) were adjusted to a similar protein content of ≈30% db, a similar fat content of ≈17% db, and a similar moisture content of ≈19% wb. With different DDGS levels (0, 10, 20, 30, 40, and 50% db), varying amounts of soybean meal, soybean oil, and celufil, but a constant level of fish meal, menhaden oil, cellulose gum, vitamin, and mineral mix, these ingredients were used to prepare nutritionally balanced diets for juvenile yellow perch. DDGS was provided by Dakota Ethanol (Wentworth, SD) and soybean meal was obtained from Dakotaland Feeds (Huron, SD). These were ground with a Wiley mill (model 4, Thomas Scientific, Swedesboro, NJ) to a flour with an average particle size of ≈500 μm. Soybean oil was purchased from Consumers Supply Distributing (Sioux City, IA); celufil (a nonnutritive filler) was obtained from USB Corporation (Cleveland, OH); menhaden fish meal from The Scoular Company (Minneapolis, MN); menhaden fish oil from Omega Protein (Houston, TX); cellulose gum (sodium carboxy methyl cellulose used as a binder) from Akzo Nobel Functional Chemicals (Netherlands); vitamin mix and mineral mix from Rangen (Buhl, ID).

Components were mixed for 10 min, combined with the soybean and menhaden oil and stirred for another 15 min in a mixer (Kushlan Products, Goldendale, WA). After all ingredients were thoroughly combined, each blend was adjusted to a desired pre-extrusion moisture content of 60–65% by adding adequate amounts of water during mixing using a laboratory scale mixer (N50, Hobart Corporation, Troy, OH).

Raw Ingredient Properties

Each raw blend was analyzed for moisture content, water activity, thermal conductivity (k), thermal diffusivity (α), and color (Hunter *L,a,b* values). Raw material from each blend was placed in a 250-mL beaker. The sensor needle of the thermal properties analyzer (KD2, Decagon Devices, Pullman, WA) was inserted into the medium, and the thermal conductivity and thermal diffusivity were measured three times on three different positions (n = 3) in the material at room temperature (20 ± 1°C).

Extrusion Processing

The extrusion processing of each blend was performed using a single-screw extruder (model PL 2000 Plasti-Corder, Brabender South Hackensack, NJ) with a compression ratio of 3:1, a screw length-to-diameter ratio of 20:1, and a barrel length of 317.5 mm. The center of the die assembly was conical and tapered from an initial diameter of 6.0 mm to a diameter of 2.95 mm at the discharge opening. The length of the die was 26.93 mm, which resulted in a die length-to-diameter ratio of 9.13. A 7.5 HP (5.5 kW) motor was connected to the extruder. The screw speed was adjusted to 230 rpm during extrusion. The temperature of the feed zone was controlled and maintained at 40°C, that of the transition zone at 90°C, and that of the die zone at 100°C during all trials.

Raw blends were manually funneled into the extruder in constant quantities to avoid jamming at the barrel throat. The mass flow rate (MFR) was determined by collecting extrudate samples at 30-sec intervals during extrusion, weighing the collected quantity on an electronic balance (PB 5001, Mettler Toledo, Switzerland), and then accounting for moisture losses at the die exit (Rosentrater et al 2005). During extrusion processing, the moisture content at the die (% db) was monitored, and the temperature (°C) of the extrudates exiting the extruder was measured with an infrared thermometer (model 42540, Extech Instruments, Waltham, MA).

Physical Properties

After the prepared blends were cooked in the extruder and then dried for 24 hr at room temperature (20 ± 1°C), they were analyzed in terms of moisture content (% db), water activity (-), unit density (kg/m^3), expansion ratio (-), compressive strength (MPa), compressive modulus (MPa), pellet durability index (%), water stability (min), color (-), and nutrient compositions (% wb, %db).

Moisture content (MC). According to Approved Method 44-19.01 (AACC International 2010), the moisture content of the raw material and extrudate samples for each blend were determined using a laboratory oven (Thelco Precision, Jovan, Winchester, VA) at 135°C for 2 hr. The same methodology was used for samples collected at the die.

Water activity (a_w). Water activity was measured for raw material and extrudate samples from each treatment with a water activity meter (Sprint TH-500, Novasina, Pfäffikon, Switzerland). A sample bowl was filled with each sample and then placed into the measuring chamber of the precalibrated instrument.

Unit density (UD). The extrudates were cut to pieces 25.4 mm long, weighed on an analytical balance (Adventurer, Ohaus, Pine Brook, NJ), then measured with a digimatic caliper (model CD-6''C, Mitutoyo, Tokyo, Japan) to determine the diameter. According to Rosentrater et al (2005) the unit density (UD, kg/m^3) was calculated as the ratio of the mass M (kg) to the volume V (m^3) of each measured and weighed extrudate sample, assuming a cylindrical shape for each extrudate: UD = M/V (Eq. 1)

Expansion ratio (ER). The ratio of the diameter of the extrudate for each blend, measured with a digimatic caliper (model CD-6''C, Mitutoyo, Tokyo, Japan), to the diameter of the die nozzle (2.95 mm) was used to quantify the radial expansion ratio.

Compressive strength and modulus. For each treatment, the extruded samples were cut into pieces ≈25.4 mm long and tested for compressive strength and modulus (stiffness) using a compression testing machine (model 5564, Instron, Canton, MA).

Pellet durability index (PDI). The pellet durability index was determined according to ASAE Method S269.4 (2004). Extrudates (≈100 g) from each blend were manually sieved (U.S.A. standard testing, ASTM E-11 specification, Daigger, Vernon Hills, IL) for ≈10 sec to remove initial fines and then tumbled in a pellet durability tester (model PDT-110, Seedburo Equipment, Chicago, IL) for 10 min. Afterwards, samples were again sieved for ≈10 sec, and weighed on an electronic balance (Explorer Pro, model EP 4102, Ohaus, Pine Brook, NJ). For blends 1–4, sieve No. 7 (2.80 mm) was used, but for blends 5 and 6 sieve No. 8 (2.36 mm) was used. PDI = (M_a/M_b) × 100 (Eq. 2); where M_a was the mass (g) after tumbling and M_b was the sample mass (g) before tumbling.

Water stability. Water stability is defined as the amount of time for a pellet to begin to break apart after it has been placed in water. For extrudates of each blend, a 1-g sample was placed in 200 mL of distilled water and gently stirred with a magnet stirrer (PMC No. 524C, Barnstead International, Dubuque, IA) until the extrudates broke, to determine the stirred water stability. For still water stability, the same process was used without stirring.

Color. A spectrophotometer (LabScan XE, HunterLab, Reston, VA) was used to determine extrudate color, where *L* quantified the brightness/darkness, *a* referred to the redness/greenness, and *b* referred to the yellowness/blueness of the samples. Likewise, the color was tested on the raw material blends.

Nutrient analysis. For each diet a single replicate (n = 1) of extrudate samples was analyzed for total moisture, total dry matter, crude protein, and crude fat following official Method 990.3, 2002.04, 920.39, and 942.05 (AOAC 2003), respectively.

Data Analysis

Each blend was extruded twice. For each extrusion run, three replicates (n = 3) were measured for all physical properties except for compressive strength, compressive modulus, unit density, and expansion ratio, where 10 measurements (n = 10) were taken, and except for water stability (both stir and still), where one replicate (n = 1) was taken. All data were analyzed using SAS v.8.0 software (SAS Institute, Cary, NC) with a Type I error rate of 0.05, by analysis of variance (ANOVA), and then post hoc LSD for the variables that exhibited significant differences.

RESULTS AND DISCUSSION

Raw Blend Analysis

Physical properties of the raw blends are provided in Table II. Average moisture content across all blends was 62.25 ± 0.37%. Owing to the high moisture content, water activity was also high (0.89 ± 0.00). Average thermal conductivity was 0.10 W/(m·°C) ± 0.01 W/(m·°C), and average thermal diffusivity was 0.11 mm^2/sec ± 0.01 mm^2/sec.

The thermal conductivity expresses the ability of a material to transfer heat by conduction. Therefore, in this study, the values were low at 0.09–0.11 W/(m·°C); they decreased insignificantly when increasing the DDGS content in the blend. Low thermal conductivity indicates poor heat transfer in a material. Thermal dif-

TABLE II
Physical Properties of Raw Feed BlendsBefore Extrusion Processing[a]

	Diet (DDGS % db)					
Properties	**0**	**10**	**20**	**30**	**40**	**50**
MC (% db)	63.75a	63.68a	64.42a	64.43a	58.02b	59.21b
	(0.56)	(0.05)	(0.70)	(0.36)	(0.20)	(0.33)
a_w (-)	0.91a	0.91a	0.90b	0.89c	0.87d	0.86e
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
k (W/m°C)	0.11a	0.10a	0.10a	0.10a	0.09a	0.09a
	(0.01)	(0.02)	(0.02)	(0.02)	(0.01)	(0.00)
α (mm^2/sec)	0.11a	0.11a	0.11a	0.11a	0.11a	0.11a
	(0.01)	(0.01)	(0.01)	(0.02)	(0.01)	(0.00)
Hunter *L*	44.54a	45.68a	45.15a	38.35bc	40.37b	36.54c
	(1.58)	(1.45)	(2.86)	(0.35)	(0.80)	(1.11)
Hunter *a*	8.41a	8.39a	9.18b	9.56bd	10.85c	10.00d
	(0.26)	(0.38)	(0.49)	(0.06)	(0.24)	(0.16)
Hunter *b*	34.05a	34.09a	34.01a	32.76a	35.97a	33.41b
	(1.15)	(1.48)	(0.98)	(0.27)	(0.57)	(0.59)

[a] Means followed by the same letters within a row are not significantly different at P < 0.05, LSD. Values in parentheses are standard deviation. MC, moisture content; a_w, water activity; k, thermal conductivity; α, thermal diffusivity; *L,a,b*, Hunter color parameters.

fusivity, on the other hand, is defined as the ratio of the thermal conductivity to the volumetric heat capacity. It is the parameter that governs time-dependent unsteady-state heat transfer (Bouguerra et al 2001) and is an indicator of thermal performance (Kawasaki and Kawai 2006). Because thermal diffusivity affects the rate of heat transfer in a material, it may affect cooking and shearing processes in the extruder. Thus, the resulting molecular structure of the final extrudates may be affected. The thermal diffusivity for all raw blends was measured at a constant level of 0.11 mm^2/sec. Therefore, it appears that the DDGS level did not interfere with the heat transfer in the extruder during processing. Thermal conductivity and diffusivity are related to the heat transport efficiency (Arámbula-Villa et al 2007). Due to low values of the blends in this study, the heating and cooling of the raw materials requires more time, which can have a negative effect on the extrusion process. On the other hand, the process is less sensitive to external thermal influences, which makes the process more stable.

Regarding color of the raw blends, Hunter *L* values were 36.54 ± 1.11 to 45.68 ± 1.45; Hunter *a* values were 8.39 ± 0.38 to 10.85 ± 0.24; *b* values were 32.76 ± 0.27 to 35.97 ± 0.57. As DDGS increased, brightness (Hunter *L*) decreased, redness (Hunter *a*) increased, whereas yellowness (Hunter *b*) remained almost steady. These changes were due to the color of the DDGS particles.

Extrusion Processing Parameters

Table III provides the processing parameter data during extrusion, including extrudate mass flow rate (MFR), and the resulting processing temperatures (in relation to set points).

Increasing the DDGS content from 0 to 10% yielded a decrease in MFR from 181.33 to 110.67 g/min. Subsequently, a steady increase in MFR from 110.67 to 270.00 g/min (an increase of 144%) was observed by raising the DDGS content from 10 to 30%. An increase from 30 to 40% DDGS content yielded a slight drop in MFR of 24.4%. Using similar ingredients, Chevanan et al (2008) observed an increase in extruder throughput when raising the DDGS content of the blends from 20 to 30% and a decrease in extruder throughput when raising the DDGS content from 30 to 40%, as well. An increase of DDGS from 40 to 50% yielded a further 50.3% increase in MFR and resulted in the highest mass flow rate for all blends, at a level of 306.7 g/min. Overall, it appeared that increasing the DDGS in the blend led to an increase in MFR, which can be related to an increase in density with higher DDGS level. Variance from this trend was probably due to either experimental error or instability in the extruder.

The mass flow rate is one way to quantify the performance of the extruder during processing. It can be influenced by the screw speed, diameter of the die (Kannadhason et al 2009c), shear rate, blend composition, level of DDGS, moisture content, and viscosity of the dough melt (Chevanan et al 2008).

Rosentrater et al (2009a) and Kannadhason et al (2009b) observed 120.5 g/min and 192.8 g/min, respectively, as the highest MFR, both using a screw speed of 200 rpm for DDGS-based extrusion studies. Compared to these results, MFR determined in this study appeared to be higher. Furthermore, it is apparent that the MFR was affected by DDGS level.

In terms of processing temperatures, all observed values for the various extruder zones (feed, transition, die) were close to the set points. DDGS level did not appear to have a clear effect. The same applied to product temperature at the die discharge.

TABLE III
Treatment Effects on Extrusion Processing Parameters[a]

Parameter	Diet (DDGS % db) 0	10	20	30	40	50
MFR (g/min)	181.33a	110.67b	114.67b	270.00c	204.00a	306.67d
	(11.02)	(23.18)	(2.31)	(28.00)	(25.06)	(7.02)
Processing temperature (°C)						
Feed (n = 40)	41.00a	39.30b	40.60ac	40.20cd	40.60ac	40.00d
	(0.00)	(0.82)	(0.52)	(0.42)	(0.70)	(0.00)
Transition (n = 90)	90.10a	89.80ab	90.90c	89.80ab	90.30ac	89.30b
	(0.74)	(0.42)	(0.88)	(0.79)	(1.06)	(0.67)
Die (n = 100)	100.00a	92.9	100.00a	102.2	100.30a	99.30a
	(0.00)	(28.82)	(0.00)	(0.79)	(0.48)	(0.48)
Discharge product	67.48a	64.42b	62.52b	63.57b	65.08ab	72.09c
	(2.73)	(3.39)	(4.16)	(3.33)	(2.86)	(1.62)

[a] Means followed by similar letters within a row are not significantly different at $P < 0.05$, LSD. Values in parentheses are standard deviation. MFR, mass flow rate.

Extrudate Properties

Table IV provides the physical properties including moisture content, water activity, unit density, expansion ratio, compressive strength, pellet durability, water stability, and color data of the resulting extrudates.

Moisture content. The moisture content (MC) of the ingredient blends typically has significant effects on extrudate properties such as water stability, pellet durability, and color. In addition, the initial MC also affects the extrusion processing parameters including mass flow rate through the extruder (Chevanan et al 2007a). For the final product, MC will impact texture and the resistance to external applied forces; at higher MC, pellets are less brittle and less fragile (Mazumder et al 2007).

An initial moisture content of the raw materials had been set at high levels (60–65%) to achieve softer and more water stable extrudates. Thus, no clear pattern of changes in MC was observed when increasing the DDGS level. Adding 10% of DDGS to the raw ingredient blend yielded a decrease from 1.26 to 0.82% in final extrudate moisture content, and therefore resulted in the lowest MC of all blends. The increase of the DDGS content from 20 to 40% did not show significant effects on pellet MC, which increased by 4.1%. However, an increase from 40 to 50% DDGS level showed a highly significant effect and resulted in an increase from 1.5 to

TABLE IV
Treatment Effects on Resulting Extrudate Physical Properties[a]

Property	Diet (DDGS % db) 0	10	20	30	40	50
MC (% db)	1.26a	0.82b	1.45a	1.31a	1.51a	5.33c
	(0.21)	(0.19)	(0.13)	(0.10)	(0.09)	(0.22)
a_w (-)	0.03a	0.02a	0.04b	0.04c	0.05b	0.18d
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
UD (kg/m^3)	878.70a	876.34a	973.10b	975.75b	1016.24bc	1030.67c
	(83.88)	(66.39)	(53.86)	(60.29)	(45.56)	(34.93)
ER (-)	1.09a	1.09a	1.04b	1.07a	1.10a	1.09a
	(0.03)	(0.05)	(0.04)	(0.02)	(0.02)	(0.02)
Comp S (MPa)	3.15a	3.06a	3.36a	3.64ab	3.54a	4.28b
	(1.21)	(0.60)	(0.73)	(0.85)	(0.46)	(0.53)
Comp M (MPa)	28.27a	48.78a	38.38a	41.99a	26.28a	41.48a
	(30.34)	(31.06)	(37.30)	(31.01)	(30.28)	(29.79)
PDI (%)	96.18a	97.63b	96.43ac	96.83abc	97.29bc	96.31a
	(0.55)	(0.29)	(0.29)	(0.28)	(0.28)	(1.05)
WS stir (min)	14.50a	25.00bd	>30c	24.00d	27.00b	>30c
	(2.12)	(0.00)	(0.00)	(0.00)	(1.41)	(0.00)
WS still (min)	29.50	>30	>30	>30	>30	>30
	(0.71)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Hunter *L* (-)	44.58a	43.97a	42.77b	41.33c	38.59d	38.36d
	(0.70)	(0.55)	(0.17)	(0.41)	(0.69)	(0.94)
Hunter *a* (-)	6.23a	6.98b	7.03b	7.67c	8.02d	8.27e
	(0.14)	(0.09)	(0.08)	(0.12)	(0.05)	(0.14)
Hunter *b* (-)	31.92a	31.18b	29.85c	30.29d	29.74c	28.67e
	(0.23)	(0.12)	(0.06)	(0.33)	(0.29)	(0.32)

[a] Means followed by similar letters within a row are not significantly different at $P < 0.05$, LSD. Values in parentheses are standard deviation. MC, moisture content; a_w, water activity; UD, unit density; ER, expansion ratio; Comp S, compressive strength; Comp M, compressive modulus; PDI, pellet durability index; WS, water stability; *L,a,b*, Hunter color parameters.

5.3% in MC. Therefore, the blend containing 50% DDGS had the highest extrudate MC. In previous studies using DDGS and whey, Chevanan et al (2009) showed a similar result when increasing the DDGS content from 20 to 40%, and determined an increase of 5.8% in the final MC of the extrudates.

Compared to the raw materials, the extrudate MC was, as expected, much lower. This reduction in the amount of water cannot only ascribed to the steam flashing at the die exit, but also because the extrudates were cooled and dried at room temperature for 24 hr (Rosentrater et al 2009a). In the extrusion process, the sudden drop from high pressure to atmospheric pressure at the die exit causes extensive water flashing-off and allows the expansion of the melt. Additionally, the radial expansion influences the internal structure of the expanding melt and therefore determines the texture of the final extrudates (Arhaliass et al 2003).

Water activity. Water activity, unlike moisture content, measures the free water existing in the material that is not bound to molecules. It influences the shelf life of a product because it provides microorganisms such as bacteria, molds, and yeast with water that supports growth; the higher the a_w, the greater the risk of rapid spoilage. Water activity is defined as the ratio of water pressure in the material to the water pressure of pure water under the same environmental condition. It specifies equilibrium relative humidity and the scale extends from 0 (completely dry) to 1.0 (pure water) (Food Science Australia 2005: http://www.foodscience.csiro.au/water_fs.htm). In general, a_w <0.6 is considered to provide a shelf-stable product with long storage stability (Lowe and Kershaw 1995).

The water activity of the raw blends was 0.86–0.91 and showed no significant differences between all blends. This was anticipated, as all blends were formulated to the same target moisture level. Likewise, a_w values for the raw blends were, as expected, high due to the initial adjusted moisture content. In terms of the extruded product, increasing the DDGS content from 10 to 50% resulted in a significant increase for a_w from 0.02 to 0.18. Even so, the values for the water activity of all extrudates were very low, and the final product was extremely dry. This can be attributed to the fact that extrudates were thoroughly air-dried after extrusion.

Unit density. Unit density is an important aspect of fish feed. It is inversely related to the expansion ratio (Ilo et al 1999); the more compact (dense) a pellet, the less expansion. Unit density thus governs product floatability, which is important for aquaculture feed (Chevanan et al 2007d).

The unit density of the extrudates was 876.34–1030.76 kg/m^3, which was an increase of 17.3%. Overall, as DDGS increased, unit density increased. There was a significant increase in unit density (11.0%) when DDGS content increased from 10 to 20%. Chevanan et al (2009) and Kannadhason et al (2009b) found that increasing DDGS levels to 20–40% resulted in no significant changes in extrudate unit density. In this study, all extrudates with a DDGS level of 0–30% had a density below that of water (1,000 kg/m^3). Even so, they did not float well and sank slowly to the beaker bottom. This can be traced back to the relatively porous structure of the pellets (Figs. 1 and 2), which rapidly absorbed the water. Unlike other cultured fish species, yellow perch are slow feeders (Webster and Lim 2002). Because they feed on or near the bottom, even in open waters (Pearse and Achtenberg 1920), floatability of the pellets is not necessarily required.

Expansion ratio. The level of extrudate expansion upon exiting the die impacts the resulting unit density, as well as the fragility and hardness of the extrudates (Rosentrater et al 2009a). As shown in Table IV, expansion levels were 1.04–1.10 and showed no significant differences, except for the treatment with 20% DDGS content. All expansion ratios were very low and this difference could be attributed to experimental error.

Expansion ratio is related to the unit density (Ilo et al 1999). Expansion depends on the flashing of water vapor and the flow properties of the molten dough at the die exit (Mercier et al 1989). DDGS naturally has a low starch content (often 4.7–5.9%) and high fiber content (Rosentrater and Muthukumarappan 2006). Thus, the higher the DDGS level in the blend, the lower the starch, and higher the fiber content. Even though these changes have the potential to hinder expansion, this did not seem to occur in this study.

Compressive strength and compressive modulus. Compression tests provide information about the capacity of pellets to resist forces without breaking or deforming. The values for compressive strength in this study were 3.06–4.28 MPa. The blend with 50% DDGS had the highest compressive strength of 4.28MPa, which was significantly different from the other blends, except the blend with 30% DDGS. The higher resistance against forces may be related to the significantly higher moisture content of the 50% blend. It can be assumed that the components were more closely bonded to each other. This is reflected in the higher unit density for this blend as well. Mazumder et al (2007) observed increasing forces applied on ready-to-eat corn balls when increasing the ingredient moisture content from 2 to 10%, but this was due to the high starch content of corn. Starch, in combination with the high water content and heat, is readily gelatinized (Avérous and Halley 2009). All compressive strength values were low, which indicated that the extrudates had a fragile structure and broke relatively easily. This may be ascribed to the relatively low starch content of the DDGS and the raw blends.

Compressive modulus is a measure of structural stiffness. There were no significant differences for the compressive moduli across the blends, which may be due to the high standard deviation for all values (i.e., we were not able to resolve differences). The means for compressive moduli were 26.28–48.78 MPa, although no trends with increasing DDGS levels were observed. These highly variable data can be explained by the fact that extrudates are complex in structure; the texture is not homogenous (Figs. 1 and 2), and they had different sized particles that induced different reactions when external forces were applied.

Pellet durability index. Pellet durability index (PDI), another physical quality parameter of feed pellets, is measured by the amount of fines generated under standardized conditions. The quality of extruded fish feed is a decisive factor for the fish production expense. During shipping and storage, pellets are subject to breakage and attrition, which results in fines in the feed. Extrudates should have a high level of resistance to fines generation (Thomas and van der Poel 1996; Hansen and Storebakken 2007). No clear pattern of changes in PDI was observed when increasing the DDGS levels. Changing the levels of DDGS yielded only minor changes in PDI. The blend including 10% DDGS yielded the highest PDI (97.63%) and resulted in a 1.5% higher PDI than the blend without DDGS. In accordance with the results from Chevanan et al (2007b), who conducted studies on twin-screw extrusion, an increase of the DDGS content from 20 to 40% did not result in significant changes in extrudate durability. The durability values for blends including DDGS were 96.31–97.63%, indicating high pellet durability indices for all blends and hence, very good resistance against destructive forces that occur during transportation and storage.

Water stability. Besides floatability, stability in water plays a decisive role for fish feed because it determines the dissolving period and thus the loss of extrudate nutrients once they are placed in water. Physical properties, blend compositions, processing methods, and the type of binders used could affect water stability of extrudates. Furthermore, the required duration of water stability depends on the time that fish need to consume their rations (Lim and Cuzon, 1994).

The time for almost all extrudates to dissolve in still water was >30 min; only the extrudates without DDGS started dissolving earlier at 29.5 min. The times that extrudates started dissolving in stirred water were lower at 14.5 min for the blend without DDGS and 24 to >30 min for the extrudates containing DDGS. Overall, all blends exhibited adequate water stability.

Color. The color of an aquafeed generally plays no decisive role for the sales market, but it can be used to assess potential damage of protein in these processed products (Björck et al 1984). Lysine, an important component in fish feed, is the most reactive amino acid in the Maillard reaction, which is caused by high temperatures in combination with low water content, and it often occurs in extrusion cooking (Björck and Asp 1983). A significant decrease of 14.0% in extrudate brightness (Hunter *L*) was observed when increasing the DDGS content from 0 to 50%; the lower the *L* value, the darker the sample. For the raw blends, no discernable trends in brightness were evident.

Regarding the changes in extrudate redness (*a*), all Hunter *a* values resulted in significant differences. Increasing the DDGS content from 0 to 50% resulted in a steady increase in Hunter *a* by 32.7%. Parallel behavior was seen in the raw blends (Table II). Similar conclusions for Hunter *a* were ascertained by Chevanan et al (2007b) for twin-screw extrusion trials using DDGS. DDGS is dark yellow-brown; an increase in DDGS content can be expected to result in darker and more brownish extrudates.

As the DDGS content was increased from 0 to 50%, the extrudate brightness (Hunter *L*) decreased by 14%, redness (Hunter *a*) increased by 33%, and yellowness (Hunter *b*) decreased by 10.2%. For the blend containing 30% DDGS, Hunter *b* was actually higher than for the blend containing 20% DDGS. This value was higher than expected and might be attributed to the high value for standard deviation for this treatment.

Comparing the change in color of the raw materials to the extrudates, brightness (Hunter *L* value) decreased (became darker) ≤5.3%, redness (Hunter *a* value) decreased (became greener) from 16.8 to 26.1%, and yellowness (Hunter *b* value) decreased (became bluer) between 6.3 and 17.3% due to extrusion processing.

Thus, it appears that the changes in color were not only affected by changes in DDGS content and ingredient composition,

Fig. 1. Extrudates produced in this study were cylindrical in shape.

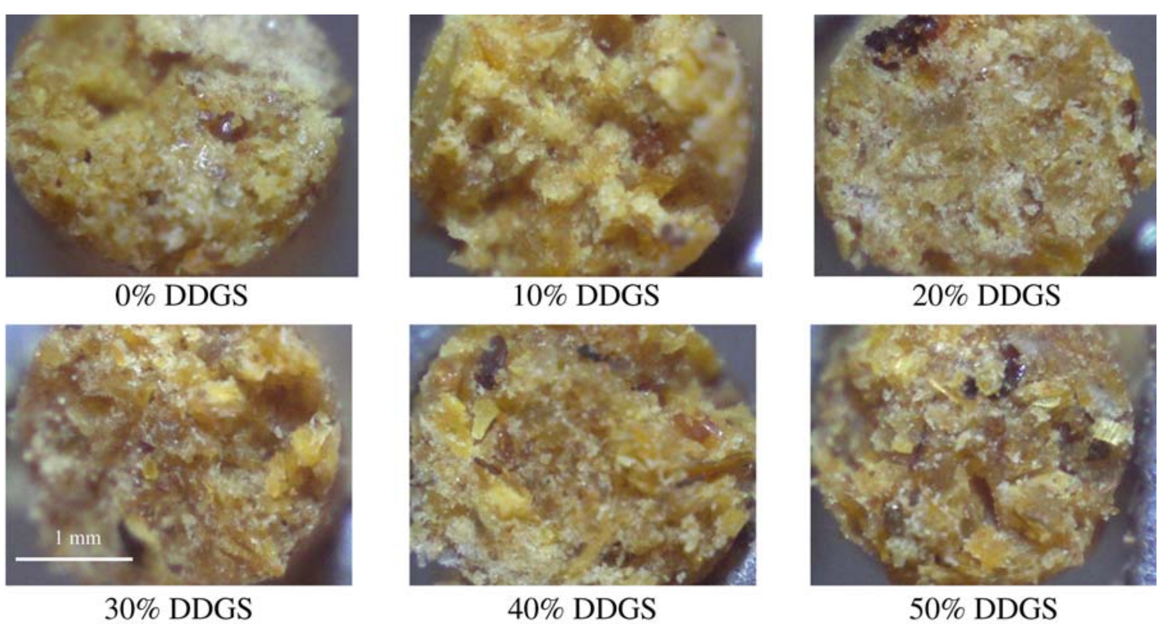

Fig. 2. Cross-sections of resulting extrudates (60X).

but were also partially affected by processing conditions, probably relating to the Maillard reaction.

Property Correlations

Pearson linear correlation analysis results can be found in Tables V, VI, and VII. Among the various properties, 25 correlations had r values > 0.80, and 28 correlations had r values < –0.8. Most of these strong linear relationships were anticipated based on results of previous research (e.g., Chevanan et al 2007b; Kannadhason et al 2009a). In this study, several color parameters were highly correlated, but these have already been discussed. Extrudate moisture content and compressive strength had an r value > 0.90. Likewise, compressive strength showed a strong positive relation to the mass flow rate (r > 0.86). It can be assumed that the less water was evaporated, the higher the mass flow rate. Hence, the moisture content was higher in the extrudates, which required higher forces to break the final product. Several strong correlations existed between the thermal conductivity of the raw blends and extrudate

TABLE V
Linear Correlations Among All Independent and Dependent Variables for Extrudate, Processing, and Raw Properties[a]

	DDGS	MC	UD	ER	Comp S
Extrudate properties					
DDGS	1				
MC	0.7109	1			
UD	0.9490	0.6241	1		
ER	0.0880	0.1307	–0.1324	1	
Comp S	0.8972	0.9049	0.8417	0.0520	1
Comp M	0.0135	0.1201	–0.1595	–0.2304	0.0720
a_w	0.7423	0.9968	0.6463	0.1187	0.9130
WS stir	0.7207	0.4446	0.7158	–0.3719	0.5359
WS still	0.6547	0.2008	0.5868	–0.2487	0.3943
PDI	0.0041	–0.4535	–0.1575	0.3601	–0.3534
L	–0.9766	–0.6623	–0.9330	–0.2242	–0.8446
a	0.9816	0.6226	0.8918	0.1575	0.8320
b	–0.9391	–0.7400	–0.9399	0.1875	–0.8638
Processing properties					
MFR	0.7110	0.7034	0.6289	0.2875	0.8643
T_{feed}	–0.1348	–0.1175	0.1244	–0.1890	–0.0609
$T_{transition}$	–0.3545	–0.5856	–0.0833	–0.6089	–0.5347
T_{die}	0.3493	0.1530	0.5521	–0.2967	0.4201
$T_{discharge}$	0.4007	0.8595	0.2636	0.5057	0.6587
Raw properties					
MC	–0.7417	–0.5657	–0.6633	–0.5627	–0.5889
a_w	–0.9593	–0.7887	–0.9009	–0.2623	–0.9233
k	–0.9616	–0.6168	–0.8787	–0.3246	–0.8135
α	0.7068	0.1502	0.6791	0.2529	0.5218
L	–0.8634	–0.7037	–0.7811	–0.2301	–0.9146
a	0.8815	0.4038	0.9099	0.1532	0.6566
b	0.0590	–0.2451	0.1076	0.3714	–0.2603

[a] DDGS, distillers dried grains with solubles; MC, moisture content; UD, unit density; ER, expansion ration; Comp S, compressive strength; Comp M, compressive modulus; a_w, water activity; WS, water stability; PDI, pellet durability index; *L,a,b*, Hunter color parameters; MFR, mass flow rate; T, temperature; *k*, thermal conductivity; α, thermal diffusivity.

TABLE V (*continued*)
Linear Correlations Among All Independent and Dependent Variables for Extrudate, Processing, and Raw Properties[a]

	Comp M	a_w	WS stir	WS still	PDI	*L*	*a*	*b*
Extrudate properties								
Comp M	1							
a_w	0.1709	1						
WS stir	0.3789	0.5044	1					
WS still	0.5239	0.2752	0.9020	1				
PDI	0.2951	–0.3957	0.1909	0.5046	1			
L	0.1725	–0.6856	–0.6188	–0.5477	–0.0284			
a	0.1047	0.6639	0.7227	0.7326	0.1804	–0.9553	1	
b	–0.1126	–0.7744	–0.8669	–0.7058	0.1186	0.8755	–0.8899	1
Processing properties								
MFR	–0.0625	0.6923	0.1054	0.1016	–0.3423	–0.6992	0.6732	–0.5384
T_{feed}	–0.8730	–0.1775	–0.3886	0.5904	–0.6287	0.0207	–0.2723	0.1280
$T_{transition}$	–0.4016	–0.5897	0.0470	–0.0602	–0.0467	0.3178	–0.4047	0.1761
T_{die}	–0.5501	0.1202	–0.0507	–0.1353	–0.5876	–0.3766	0.2434	–0.2967
$T_{discharge}$	–0.0721	0.8301	–0.0183	–0.2281	–0.4398	–0.4258	0.3230	–0.3377
Raw properties								
MC	0.3978	–0.5733	–0.3740	–0.2569	–0.1310	0.8505	–0.7227	0.6117
a_w	0.1581	–0.8008	–0.5322	–0.4243	0.1299	0.9756	–0.9172	0.8578
k	0.1173	–0.6441	–0.5738	–0.5649	–0.1404	0.9874	–0.9573	0.8198
α	–0.2262	0.1701	0.2330	0.4152	0.2302	–0.7479	0.7525	0.4720
L	0.0055	–0.7113	–0.3380	–0.3495	0.1809	0.8418	–0.8442	0.7061
a	–0.3781	0.4250	0.5505	0.5091	0.1024	–0.9417	0.8641	–0.7699
b	–0.6335	–0.2423	0.0562	–0.0010	0.4066	–0.2311	0.0709	0.0013

[a] Comp M, compressive modulus; a_w, water activity; WS, water stability; PDI, pellet durability index; *L,a,b*, Hunter color parameters; MFR, mass flow rate; T, temperature; MC, moisture content; *k*, thermal conductivity; α, thermal diffusivity.

TABLE VI
Linear Correlations Among All Independent and Dependent Variables for Processing Properties and Raw Properties[a]

	MFR	T_{feed}	$T_{transition}$	T_{die}	$T_{discharge}$
Processing properties					
MFR	1				
T_{feed}	0.0533	1			
$T_{transition}$	–0.6822	0.5349	1		
T_{die}	0.5510	0.7457	0.2001	1	
$T_{discharge}$	0.6368	–0.0292	–0.7088	0.0106	1
Raw properties					
MC	–0.4643	–0.0351	0.2894	–0.0980	–0.5532
a_w	–0.8054	–0.0029	0.4455	–0.4010	–0.5950
k	–0.7167	0.1163	0.4079	–0.3101	–0.4137
α	0.6757	0.0627	–0.2498	0.5544	0.0053
L	–0.9626	0.0470	0.6135	–0.5154	–0.5341
a	0.5466	0.1724	–0.0421	0.4929	0.1702
b	–0.3528	0.2645	0.4249	–0.1232	–0.1309

[a] MFR, mass flow rate; T, temperature; MC, moisture content; a_w, water activity; k, thermal conductivity; α, thermal diffusivity; *L,a,b*, Hunter color parameters.

TABLE VII
Linear Correlations Among All Independent and Dependent Variables for Raw Properties[a]

	MC	a_w	k	α	L	a	b
Raw properties							
MC	1						
a_w	0.8313	1					
k	0.8466	0.9589	1				
α	–0.5089	–0.6837	–0.7976	1			
L	0.5665	0.8995	0.8586	–0.7794	1		
a	–0.8092	–0.8646	–0.9223	0.8164	–0.7095	1	
b	–0.5870	–0.1019	–0.2192	0.1182	0.2451	0.4237	1

[a] MC, moisture content; a_w, water activity; k, thermal conductivity; α, thermal diffusivity; *L,a,b*, Hunter color parameters.

properties. The thermal conductivity was very strongly and negatively correlated to the DDGS content, with $r < –0.96$. A strong positive correlation between thermal conductivity and moisture content and water activity of the raw blends was observed with $r > 0.84$. These could be ascribed to thermal conductivity of water, which has an average value of 0.6 W/(m·°C), which is higher than the values determined in the raw blends.

CONCLUSIONS

This study was conducted with the goal of producing water-stable feeds for juvenile yellow perch by enhancing the amount of DDGS, with constant protein content (30.1%), using similar feed moisture content (60–65%), and constant extruder settings. Changing the levels of DDGS had significant effects on extrudate unit density, water activity, color (Hunter *L,a,b*), and on the raw material water activity and color. The mass flow rate generally increased when raising the DDGS content of the blends. The expansion ratio of all blends was low, as expected, due to the low starch content of the DDGS and high moisture of the feed blends.

The extruded materials had low compressive strength. In contrast, the PDI values were high, and thus the pellets were highly resistant to destructive forces. The combination of low compressive strength and high PDI provides pellets with excellent transport properties that are easily consumable as feed for the fish. Moreover, results showed very good water stability; it took at least 30 min before the extrudates would dissolve in water.

All pellets showed significant changes in color after extrusion due to the processing conditions; this was partially attributable to the changes in the composition of the raw materials before processing.

In summary, the investigation yielded high quality extrudates. Continuing work is focusing on testing of acceptability in actual fish diets and resulting growth performance, but those results are reported elsewhere.

ACKNOWLEDGMENTS

We thank the Agricultural Experiment Station, South Dakota State University, and the North Central Agricultural Research Laboratory, USDA ARS, Brookings, SD, for funding, facilities, equipment and supplies. Furthermore, the cooperation and assistance of Sharon Nichols, Christine Keierleber, Steve Schacht, Travis Schaeffer, and Vanja Jurisic is greatly appreciated. Their contributions have helped bring this project to completion.

LITERATURE CITED

Ali, A., Al-Asgah, N. A., Al-Ogaily, S. M., and Ali, S. 2003. Effect of feeding different levels of alfalfa meal on the growth performance and body composition of Nile tilapia (*Oreochromis niloticus*) fingerlings. Asian Fish. Soc. 16:59-67.

AOAC. 2003. Official Methods of Analysis of the Association of Official Analytical Chemists International, 17th Ed. The Association: Gaithersburg, MD.

Arámbula-Villa, G., Guitiérrez-Árias, E., and Moreno-Martínez, E. 2007. Thermal properties of maize masa and tortillas with different components from maize grains, and additives. J. Food Eng. 80:55-60.

Arhaliass, A., Bouvier, J. M., and Legrand, J. 2003. Melt growth and shrinkage at the exit of the die in extrusion-cooking process. J. Food Eng. 60: 185-192.

Arndt, R. E., Hardy, R. W., Sugiura, S. H., and Dong, F. M. 1999. Effects of heat treatment and substitution level on palatability and nutritional value of soy defatted flour in feeds for Coho salmon, *Oncorhynchus kisutch*. Aquaculture 180:129-145.

ASAE. 2004. Engineering practices and data standards of the American Society of Agricultural Engineers. The Society: St. Joseph, MI.

Avérous, L., and Halley, P. J. 2009. Biocomposites based on plasticized starch. Biofuels Bioprod. Biorefining 3:329-343.

Björck, I., and Asp, N.-G. 1983. The effects of extrusion cooking on nutritional value—A literature review. J. Food Eng. 2:281-308.

Björck, I., Asp, N.-G., and Dahlqvist, A. 1984. Protein nutritional value of extrusion-cooked wheat flours. Food Chem. 15:203-214.

Bouguerra, A., Aït-Mokhtar, A., Amiri, O., and Diop, M. B. 2001. Measurement of thermal conductivity, thermal diffusivity and heat capacity of highly porous building materials using transient plane source technique. Int. Commun. Heat Mass Transfer 28:1065-1078.

Brown, P. B., Dabrowski, K., and Garling, D. L. 1996. Nutrition and feeding of yellow perch (*Perca flavescens*). J. Appl. Ichthyol. 12:171-174.

Chang, Y. K., and Wang, S. S. 1998. Advances in Extrusion Technology. Technomic Publishing: Lancaster, PA.

Cheftel, J. C. 1986. Nutritional effects of extrusion-cooking. Food Chem. 20:263-283.

Cheng, Z. J., and Hardy, R. W. 2004. Nutritional value of diets containing distiller's dried grain with solubles for rainbow trout, O*ncorhynchus mykiss*. J. Appl. Aquac. 15:101-113.

Chevanan, N., Muthukumarappan, K., Rosentrater, K. A., and Julson, J. L. 2007a. Effect of die dimensions on extrusion processing parameters and properties of DDGS-based aquaculture feeds. Cereal Chem. 84:389-398.

Chevanan, N., Rosentrater, K. A., and Muthukumarappan. K. 2007b. Twin-screw extrusion processing of feed blends containing distillers dried grains with solubles (DDGS). Cereal Chem. 84:428-436.

Chevanan, N., Muthukumarappan, K., and Rosentrater, K. A. 2007c. Neural network and regression modeling of extrusion processing parameters and properties of extrudates containing DDGS. Trans. ASABE 50:1765-1778.

Chevanan, N., Rosentrater, K. A., and Muthukumarappan, K. 2008. Effect of DDGS, moisture content, and screw speed on physical properties of extrudates in single-screw extrusion. Cereal Chem. 85:132-139.

Chevanan, N., Muthukumarappan, K., and Rosentrater, K. A. 2009. Extrusion studies of aquaculture feed using distillers dried grains with solubles and whey. Food Bioprocess. Technol. 2:177-185.

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

Coyle, S. D., Mengel, G. J., Tidwell, J. H., and Webster, C. D. 2004. Evaluation of growth, feed utilization, and economics of hybrid tilapia, *Oreochromis niloticus* × *O. aureus*, fed diets containing different protein sources in combination with distillers dried grains with solubles. Aquac. Res. 35:365-370.

Davies, D. A., and Arnold, C. R. 2000. Replacement of fish meal in practical diets for the Pacific white shrimp, *Litopenaeus vannamei*. Aquaculture 185:291-298.

El-Saidy, D. M. S. D., and Gaber, M. M. A. 2002. Complete replacement of fish meal by soybean meal with dietary L-lysine supplementation for Nile tilapia *Oreochromis niloticus* (L.) fingerlings. J. World Aquac. Soc. 33:1119-1127.

Floreto, E. A. T., Bayer, R. C., and Brown, P. B. 2000. Effects of soybean-based diets, with and without amino acid supplementation, on growth and biochemical composition of juvenile American lobster, *Homarus americanus*. Aquaculture 189:211-235.

Francis, G., Makkar, H. P. S., and Becker, K. 2001. Antinutritional factors present in plant-derived alternate fish feed ingredients and their effects in fish. Aquaculture 199:197-227.

Garduño-Lugo, M., and Olvera-Novoa, M. Á. 2008. Potential of the use of peanut (*Arachis hypogaea*) leaf meal as a partial replacement for fish meal in diets for Nile tilapia (*Oreochromis niloticus* L.). Aquac. Res. 39:1299-1306.

Goda, A. M., El-Haroun, E. R., and Kabir Chowdhury, M. A. 2007. Effect of totally or partially replacing fish meal by alternative protein sources on growth of African catfish *Clarias gariepinus* (Burchell, 1822) reared in concrete tanks. Aquac. Res. 38:279-287.

González, S., Flick, G. J., O'Keefe, S. F., Duncan, S. E., McLean, E., and Craig, S. R. 2006. Composition of farmed and wild yellow perch (*Perca flavescens*). J. Food Comp. Anal. 19:720-726.

Guimarães, I. G.,Pezzato, L. E., and Barros, M. M. 2008. Amino acid availability and protein digestibility of several protein sources for Nile tilapia, *Oreochromis niloticus*. Aquac. Nutr. 14:396-404.

Hansen, J. Ø., and Storebakken, T. 2007. Effects of dietary cellulose level on pellet quality and nutrient digestibilities in rainbow trout (*Oncorhynchus mykiss*). Aquaculture 272:458-465.

Ilo, S., Berghofer, E., and Liu, Y. 1999. Extrusion cooking of rice flour and amaranth blends. Lebens. Wiss. Technol. 32:79-88.

Jacques, K. A., Lyons, T. P., and Kelsall, D. R. 2003. The Alcohol Textbook, 4th Ed. Page 379. University Press: Nottingham, UK.

Kannadhason, S., Muthukumarappan, K., and Rosentrater, K. A. 2009a. Effect of starch sources and protein content on extruded aquaculture feed containing DDGS. Food Bioprocess. Technol. DOI: 10.1007/s11947-008-0177-4.

Kannadhason, S., Muthukumarappan, K., and Rosentrater, K. A. 2009b. Effects of ingredients and extrusion parameters on aquafeeds containing DDGS and tapioca starch. J. Aquac. Feed Sci. Nutr. 1:6-21.

Kannadhason, S., Rosentrater, K. A., and Muthukumarappan, K. 2010. Twin screw extrusion of DDGS-based aquaculture feeds. J. World Aquac. Soc. 41:1-15.

Kasper, C. S., Watkins, B. A., and Brown, P. B. 2007. Evaluation of two soybean meals fed to yellow perch (*Perca flavescens*). Aquac. Nutr. 13: 431-438.

Kawasaki, T., and Kawai, S. 2006. Thermal insulation properties of wood-based sandwich panel for use as structural insulated walls and floors. J. Wood Sci. 52:75-83.

Lim, C., and Cuzon, G. 1994. Water stability of shrimp pellet: A review. Asian Fish. Sci. 7:115-127.

Lowe, J. A., and Kershaw, S. J. 1995. Water activity-moisture content relationship as a predictive indicator for control of spoilage in commercial pet diet components. Anim. Feed Sci. Technol. 56:187-194.

Mazumder, P., Roopa, B. S., and Bhattacharya, S. 2007. Textural attributes of a model snack food at different moisture contents. J. Food Eng. 79:511-516.

Mercier, C., Linko, P., and Harper, J. M. 1989. Extrusion cooking of starch and starchy products. Pages 247-319 in: Extrusion Cooking. AACC International: St. Paul, MN.

Moscicki, L., and van Zuilichem, D. J. 1983. Animal feed applications of extrusion cooking and a Polish example. J. Food Eng. 2:211-223.

Opstvedt, J., Nygård, E., Samuelsen, T. A., Venturini, G., Luzzana, U., and Mundheim, H. 2003. Effect on protein digestibility of different processing conditions in the production of fish meal and fish feed. J. Sci. Food Agric. 83:775-782.

Øverland, M., Sørensen, M., Storebakken, T., Penn, M., Krogdahl, Å., and Skrede, A. 2009. Pea protein concentrate substituting fish meal or soybean meal in diets for Atlantic salmon (*Salmo salar*)—Effect on growth performance, nutrient digestibility, carcass composition, gut health, and physical feed quality. Aquaculture 288:305-311.

Pearse, A. S., and Achtenberg, H. 1920. Habits of yellow perch in Wisconsin lake. Bull. U.S. Bur. Fish. 36:293-366.

Ramseyer, L. J., and Garling, Jr., D. L. 1998. Effects of dietary protein to metabolizable energy ratios and total protein concentrations on the performance of yellow perch *Perca flavescens*. Aquac. Nutr. 4:217-223.

Riaz, M. N. 2000. Extruders in Food Applications. Technomic Publishing: Lancaster, PA:

Rosentrater, K. A., and Muthukumarappan, K. 2006. Corn ethanol coproducts: Generation, properties, and future prospects. Int. Sugar J. 108: 648-657.

Rosentrater, K. A., Richard, T. L., Bern, C. J., and Flores, R. A. 2005. Small-scale extrusion of corn masa by-products. Cereal Chem. 82:436-446.

Rosentrater, K. A., Muthukumarappan, K., and Kannadhason, S. 2009a. Effects of ingredients and extrusion parameters on aquafeeds containing DDGS and potato starch. J. Aquac. Feed Sci. Nutr. 1:22-38.

Rosentrater, K. A., Muthukumarappan, K., and Kannadhason, S. 2009b. Effects of ingredients and extrusion parameters on properties of aquafeeds containing DDGS and corn starch. J. Aquac. Feed Sci. Nutr. 1:39-43.

Samocha, T. M., Davis, D. A., Saoud, I. P., and DeBault, K. 2004. Substitution of fish meal by co-extruded soybean poultry by-product meal in practical diets for the Pacific white shrimp, *Litopenaeus vannamei*. Aquaculture 231:197-203.

Shapawi, R., Ng, W.-K., and Mustafa, S. 2007. Replacement of fish meal with poultry by-product meal in diets formulated for the humpback grouper, *Cromileptes altivelis*. Aquaculture 273:118-226.

Storebakken, T., Baeverfjord, G., Skrede, A., Olli, J. J., and Berge, G. M. 2004. Bacterial protein grown on natural gas in diets for Atlantic salmon, *Salmo salar*, in freshwater. Aquaculture 241:413-425.

Thomas, M., and van der Poel, A. F. B. 1996. Physical quality of pelleted animal feed. 1. Criteria for pellet quality. Anim. Feed Sci. Technol. 61:89-112.

Thompson, K. R., Rawles, S. D., Metts, L. S., Smith, R., Wimsatt, A., Gannam, A. L., Twibell, R. G., Johnson, R. B., Brady, Y. J., and Webster, C. D. 2008. Digestibility of dry matter, protein, lipid, and organic matter of two fish meals, two poultry by-product meals, soybean meal, and distiller's dried grains with solubles in partial diets for sunshine bass, *Morone chrypsops* × *M. saxatilis*. J. World Aquac. Soc. 39:352-363.

Tidwell, J. H., Webster, C. D., Yancey, D. H., and D'Abramo, L. R. 1993. Partial and total replacement of fish meal with soybean meal and distillers' by-products in diets for pond culture of the freshwater prawn

(*Macrobrachium rosenbergii*). Aquaculture 118:119-130.
Tudor, K. W., Rosati, R. R., O'Rourke, P. D., Wu, Y. V., Sessa, D., and Brown, P. 1996. Technical and economical feasibility of on-farm fish feed production using fishmeal analogs. Aquacult. Eng. 15:53-65.
Viola, S., Mokady, S., Rappaport, U., and Arieli, Y. 1981. Partial and complete replacement of fish meal by soybean meal in feeds for intensive culture of carp. Aquaculture 26:223-236.
Voca, N., Varga, B., Kricka, T., Curic, D., Jurisic, V., and Matin, A. 2009. Progress in ethanol production from corn kernel by applying cooking pre-treatment. Bioresource Technol. 100:2712-2718.
Webster, C. D., and Lim, C. E. 2002. Percids. Page 227 in: Nutrient Requirements and Feeding of Finfish for Aquaculture. CABI: Wallingford, Oxford.
Webster, C. D., Tidwell, J. H., and Yancey, D. H. 1991. Evaluation of distillers' grains with solubles as a protein source in diets for channel catfish. Aquaculture 96:179-190.
Webster, C. D., Yancey, D. H., and Tidwell, J. H. 1992. Effect of partially or totally replacing fish meal with soybean meal on growth of blue catfish (*Ictalurus furcatus*). Aquaculture 103:141-152.
Wilson, R. P., and Poe, W. E. 1985. Effects of feeding soybean meal with varying trypsin inhibitor activities on growth of fingerling channel catfish. Aquaculture 46:19-25.

[Received August 25, 2010. Accepted November 11, 2010.]