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The effects of extrusion processing of distillers dried grains with solubles (DDGS)-based yellow perch (Perca flavescens) feeds

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Abstract. 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 (31.5% db) ingredient blends were formulated with 0, 10, 20, 30, 40, and 50% distillers dried grains with solubles (DDGS) at a feed moisture content of 60-65% db, with appropriate amounts of soybean meal, fish meal, vitamin and mineral mix. Extrusion cooking was performed using a laboratory-scale single screw extruder at a constant barrel temperature profile of 40°C-90°C-100°C, and a constant screw speed of 230 rpm (24.1 rad/s). During processing the mass flow rate was determined, which 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 varying DDGS content on the physical properties of the final extrudates. Significant differences (P<0.05) between the blends were
observed for color and water activity of the raw and extruded material, and for the unit density of the extruded product. There were significant changes in brightness (L), redness (a) and yellowness (b) between 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 indices. Overall, each of the ingredient blends resulted in viable extrudates.

**Keywords.** Aquaculture, DDGS, Extrudates, Physical Properties, Protein, Single screw extruder, Yellow perch
Introduction

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 its growth rate peak at 2% per year in 1965-1970 (FAO, 2008; United Nations, 2007; United Nations, 2008; PRB, 2008). Comparing the production in the early 1950s to that in 2006, it grew from 1 million tones per year to over 51 million tones with a value of over 78 billion US dollars (FAO, 2009). The worlds increasing demands on seafood involve rising needs of fish feed in aquaculture. Commonly, high amounts of fish meal are used in diets to provide fish with proteins that are essential for their organism and metabolism. Since fish meal is a highly questioned good, fish feed becomes not only a limiting factor in production costs, but is also limited in sources. Investigators have to look for an alternative source for fish meal to stay competitive and survive. Much research has been pursued to find a reasonable, cost efficient and compatible alternative for protein in fish feed.

Goda et al. (2007) found that equivalent effects on growth and food utilization could be achieved in experiments by replacing fish meal totally by poultry by-product meals (PBM) in diets for African catfish. It has to be considered that the composition and quality of PBM varies, since 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 compared to feeding fish meal, which might be due to an insufficient amino acid content of PBM.

There are other studies in progress searching for partial replacement of fish meal, such as using bacterial protein meal (BPM) as a feed ingredient. BPM could replace high-quality fish meal up to 25% in diets for juvenile Atlantic salmon in fresh water (Storebakken et al., 2004) and levels up to 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 (Storebakken et al., 2004). Another undesirable side effect has been reported in reduced digestibility of nitrogen, lipid and energy when increasing the level of BPM (Aas et al., 2006).

A special focus of research in recent years has been on plant protein sources, which are mostly cheap in price, easy to obtain, and have a consistent composition compared to meat or poultry by-products. For example, partial replacement trials were conducted using cottonseed meal,
peanut leaf meal, corn gluten meal, pea protein concentrate, alfalfa compositions and many more 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 its low price, soybean meal (SBM) is one of the most widely used 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 anti-nutritional 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).

A further alternative for fish meal may be distillers dried grains with solubles (DDGS), which is the residual leftover of corn kernel fermentation in fuel ethanol production. Due to changes in energy policies, the ethanol industry is rapidly growing (Renewable Fuels Association, 2009a; Voca et al., 2009) and therefore, increasing amounts of DDGS are available. The U.S. Ethanol Biorefineries production of DDGS has risen from 2.3 million tons in 1999 to 23.0 in 2008 (Renewable Fuels Association 2009b). These quantities can be a sustainable resource for alternative protein in fish feed. DDGS has been fed traditionally to ruminant animals for over a century now (USDA, 2006). In contrast to corn they contain approximately three times the amount of most nutrients, such as fat, protein and minerals, as a result of the fermentation process (Jacques et al., 2003). In addition, DDGS contains no anti-nutritional factors compared to SBM (U.S. Grains Council, 2008). Preceding research with DDGS, which usually contains between 27-33% protein and 5-12% crude fiber (Belyea et al., 2004; 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 up to 50% of fish meal in fish feed for rainbow trout and then improved the substitution up to 75% by adding lysine and methionine. Furthermore, successful trials have been conducted with partial and total replacement of fish meal by SBM in combination with DDGS for fish meal in freshwater prawn (Tidwell et al., 1993).
Yellow perch (*Perca flavescens*) is a small-sized, low-fat fish whose demand is growing in the Great Lakes area of the U.S. (González et al., 2006). The diets that have been generally recommended were based upon the requirements for trout and salmon, which contain a minimum of 36% crude protein (Brown et al., 1996), as there have only been a few nutritional studies undertaken for yellow perch feed. Ramseyer and Garling (1998) determined that protein levels in the range of 210-270 g/kg dry diet, with appropriate contents of amino acids and carbohydrates, should be suitable for yellow perch diet instead of higher and commonly used amounts of 400 g/kg dry diet. So far, research for alternative protein sources in diets for yellow perch has only been performed by Kasper et al. (2007). They concluded that yellow perch were able to effectively utilize diets containing solvent-extracted, dehulled and expelled-extruded soybean meal, with a conservative recommendation of 300 g/kg diet. Therefore, fish meal protein could be successfully replaced. To date, no trials of partial or complete fish meal replacement using DDGS for yellow perch have been carried out. But a few studies have been conducted on the processing of DDGS-based feed. In previous studies, Chevanan et al. (2007a, 2007b, 2007c, 2007d, 2008a, 2008b), Rosentrater et al. (2009a, 2009b) and Kannadhason et al. (2009a, 2009b, 2009c) investigated how die dimensions, screw speed and barrel temperatures of the extruder, ingredient moisture and DDGS content of the blends effected the extrudates’ physical properties and extrusion processing parameters from single and twin-screw extruders. Chevanan et al. (2008b) showed that ingredient moisture content and screw speed had significant effects on extrudates durability and color, extruder’s throughput and that DDGS could be included successfully up to 40% in the diet. In twin-screw studies, Chevanan et al. (2007b) achieved a DDGS inclusion level up to 60% that resulted in increased moisture content, unit density, fiber and fat content but decreased durability and expansion ratio. Industrial-scale extrusion cooking of animal feed began between 1955 and 1960 (Moscicki and van Zuilichem, 1983). Extrusion is performed at high temperatures for a short residence time, with high pressures, under high shear forces, and results in modifying and texturizing the functional properties of food ingredients, respectively. Additionally, it inactivates several anti-nutritional factors, 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 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 the extrudates and on extruder processing parameters.

**MATERIALS AND METHODS**

*Feed blend preparation*

Six isocaloric (~ 3.20 kcal/g) ingredient blends 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 contents of DDGS (0, 10, 20, 30, 40, and 50% db), varying amounts of soybean meal, soybean oil and celuil, but a constant ratio of fish meal, Menhaden oil, cellulose gum, vitamin and mineral mix (Table 1), all diets were used to prepare nutritionally balanced diets for juvenile yellow perch. DDGS was provided by Dakota Ethanol LLC (Wentworth, SD) and soybean meal was obtained from Dakotaland Feeds, LLC (Huron, SD). These were ground with a Wiley Mill (Thomas Scientific, Swedesboro, NJ) to a powder with an average particle size of approximately 500 µm. The soybean oil was purchased from Consumers Supply Distributing Co. (Sioux City, IA); celuil (used as a fiber source) from USB Corporation (Cleveland, OH); fish meal from The Scoular Company (Minneapolis, MN); Menhaden fish oil from Omega Protein, Inc. (Houston, TX); cellulose gum (sodium carboxy methyl cellulose) from Akzo Nobel Functional Chemicals AB (Netherlands); vitamin mix and mineral mix from Rangen Inc. (Buhl, ID).

The components were mixed for a period of 10 min and then merged with the soybean and Menhaden oil and stirred for another 15 min in a mixer (Kushlan Products, Inc., Goldendale, WA). After all ingredients were mixed together, the blend was adjusted to a desired moisture content of 60-65% by adding adequate amounts of water during mixing.

*Raw ingredient properties*

Each raw blend was analyzed for thermal conductivity (k) and thermal diffusivity (α). From each blend, raw material was placed in a 250 mL beaker. The sensor needle of the thermal properties analyzer (KD2 Thermal Properties Analyzer, Decagon Devices, Inc., Pullman, WA) was inserted into the medium and the thermal conductivity and thermal diffusivity were measured three times on three different positions in the material at room temperature (20±1°C).

*Extrusion processing*

The extrusion studies were performed using a single-screw extruder (Brabender Plasti-Corder, model PL 200, South Hackensack, NJ) at a compression ratio 1:3, with 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 to a diameter of 6.0 mm at the opening of the die insert. The diameter of the die was 2.95 mm and 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. The temperature of the feed zone was controlled and maintained at 40 ºC, that of the transition zone at 90 ºC and that of the die at 100 ºC during all trials.

**Mass flow rate (MFR)**

The raw blends were funneled into the extruder manually in constant quantities to avoid a jam at the opening to the barrel. The mass flow rate was determined by collecting extrudates samples at 30 s intervals during extrusion and afterwards weighing on an electronic balance (PB 5001, Mettler Toledo, Switzerland).

**Physical properties**

After the prepared blends were cooked in the extruder and then dried for 24 h at room temperature (20±1 ºC), they were then analyzed in terms of their moisture content (% db), unit density (kg/m³), expansion ratio (-), compressive strength (MPa), compressive modulus (MPa), water activity (-), water stability (min), pellet durability index (%), length and diameter (mm), color (-), and nutrient (% wb, %db). Furthermore, during extrusion processing the moisture content at the die (% db) was monitored and the temperature (ºC) of the extrudates exiting the extruder was measured with an infrared thermometer (Model 42540, Extech Instruments Corporation, Waltham, MA).

**Moisture content (MC)**

According to AACC method 44-19 (2000), 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 ºC for 2 h. The same methodology was used for the raw material.

**Water activity (a_w)**

The raw material and extrudate samples from each treatment were used to determine the water activity with an a_w measuring system (aw Sprint TH-500, Novasina, Pfäffikon, Switzerland). A sample bowl was filled with each sample and then placed in the measuring chamber of the instrument.
Unit density (UD)

The extrudates were cut into 25.4 mm long pieces, weighed on an analytical balance (Adventurer™, Item No: AR 1140, Ohaus Corp. Pine Brook, NJ) and measured with a digital caliper (Digimatic caliper, Model No: CD-6”C, Mitutoyo Corp., Tokyo, Japan) to determine their diameter. According to Rosentrater et al. (2005) the unit density was calculated as the ratio of the mass $M$ (kg) to the volume $V$ (m$^3$) of each measured and weighed sample, assuming a cylindrical shape for each extrudate:

$$UD = \frac{M}{V} \quad (1)$$

Expansion ratio (ER)

The ratio of the diameter of the extrudates for each blend, measured with a digital caliper (Digimatic caliper, Model No: CD-6”C, Mitutoyo Corp., Tokyo, Japan), to the diameter of the die nozzle (2.95 mm) was used to determine the expansion ratio.

Compressive strength and modulus

For each treatment the extruded samples were cut into pieces approximately 25.4 mm in length and tested for their compressive strength and modulus (i.e. stiffness) using a dual column universal materials testing machine (Model No. 5564, Instron, Canton, MA).

Pellet durability index (PDI)

The pellet durability index was determined according to Method S269.4 (ASAE 2004). Approximately 100 g extrudate samples of each blend were manually sieved (U.S.A. standard testing, ASTM E-11 specification, Daigger, Vernon Hills, IL) for about 10 s and then tumbled in a pellet durability tester (model PDT-110, Seedburo Equipment Company, Chicago, IL) for 10 min. Afterwards the samples were again sieved for approx. 10 s and weighed on an electronic balance (Explorer Pro, Model: EP4102, Ohaus, Pine Brook, NJ). For blend 1-4 sieve No. 7 (2.80 mm) was used, but for blend 5 and 6 sieve No. 8 (2.36 mm) was used. Relating the extrudates sample weights before and after tumbling, the PDI was calculated as

$$PDI = \left( \frac{M_a}{M_b} \right) \times 100 \quad (2)$$

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 that it takes for a pellet to begin to break 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 stirred with a magnet stirrer (PMC No. 524C, Barnstead International, Dubuque, IA) until the extrudates broke to determine the stirred water stability. In the case of still water stability, the same process was used without stirring.

Color

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

Nutrient Analysis

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

RESULTS AND DISCUSSION

All data were analyzed using SAS software (SAS Institute, Cary, NC) using Type III error rate of 0.05 by analysis of variance (ANOVA) and LSD.

Raw blend analysis

Thermal conductivity and thermal diffusivity

The thermal conductivity expresses the ability of a material to transfer heat by conduction. In these studies the values ranged between 0.09 and 0.11 W/m·ºC and were therefore low; they decreased insignificantly when increasing the DDGS content of the blends. Low thermal conductivity indicates poor heat transfer in the material like insulating materials do. The thermal diffusivity affects the rate of heat transfer and may cause undesirable interactions with the shearing process in the extruder. The composition of the blend is not affected, but other physical properties such as the molecular structure of the material may be
affected. The thermal diffusivity for the raw materials was measured at a constant level of 0.11 mm²/s for all blends. Therefore, it can be assumed that the raw material did not interfere with the shearing actions in the extruder during processing. Low thermal diffusivities mean better warmth-keeping performance regarding the insulation in the non-steady-state condition of heat flow (Kawasaki and Kawai, 2006). It takes more time to heat up the blends; the heat is stored longer in the material. Thermal conductivity and diffusivity are related to the heat transport efficiency (Arámbula-Villa et al., 2007). Due to low values the heating or cooling of the raw materials requires more time, which has a negative effect on the process. On the other hand, the process is less sensitive to external thermal influences, which makes the process more stable.

**Extrusion processing parameters**

**Mass flow rate**

The mass flow rate quantifies the performance of the extruder during processing and gives conclusions about the amount of extrudates being produced in g/min. It is influenced by the screw speed, the diameter of the die (Kannadhason et al., 2009c), shear rate, level of DDGS, moisture content and viscosity of the dough (Chevanan et al., 2008b). The higher and faster the yield in producing extrudates, the better is the profitability. Increasing the DDGS content from 0 to 10% yielded a decrease of 181.11 to 110.67 g/min in MFR, whereas no differences of the MC of the extrudates occurred when adding 10% DDGS to the blends. Subsequently, a steady increase in MFR of 110.67 to 270 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 in a drop of MFR of 32.3%. Chevanan et al. (2008b) observed as well an increase in extruder throughput when raising the DDGS content from 20 to 30% and a decrease in extruder throughput when raising the DDGS content of the blends from 30 to 40%. Overall, they ascertain an increase in throughput when the moisture content was raised from 15 to 25%.

An increase from 40 to 50% DDGS content yielded a further 50% increase and resulted in the highest mass flow rate for all blends at a level of 306.7 g/min. The lowest MFR was recorded at 110.7 g/min for the blend containing 10% DDGS.

Compared to previous studies containing DDGS that were conducted by Rosentrater et al. (2009a), who determined 120.5 g/min as the highest MFR with a screw speed of 200 rpm, and Kannadhason et al. (2009b), who observed 192.8 g/min as the highest MFR level, the results
achieved in this study were high and resulted therefore in a high product yield. Furthermore, it can be approved that the MFR is affected by DDGS level and moisture content of the blends.

**Extrudate properties**

**Moisture content**

The moisture content of the raw ingredient blends has significant effects on extrudates' properties such as pellet durability, mass flow rate, and color. In addition, the initial MC also affects all extrusion processing parameters except unit density (Chevanan et al., 2007a). For the final product, the MC determines the texture and the resistance of extrudates when forces are applied; 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 between 60-65% to achieve softer and more durable extrudates. 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 1.25% to 0.82% in extrudates moisture content and resulted therefore in the lowest MC of all blends. The increase of the DDGS content from 20 to 40% did not show significant effects on pellets’ MC, which increased 4.1%. In previous studies including DDGS and whey, Chevanan et al. (2007d) came to a similar result by determining an increase of 5.8% in the final MC of the extrudates. However, an increase from 40-50% showed a highly significant effect and resulted in an increase from 1.5% to 5.3% MC. Therefore, the blend containing 50% DDGS had the highest MC of 5.33%.

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

**Water activity**

The water activity, unlike moisture content, measures the free water existing in the material, which is not bound to molecules. It determines the shelf life of a product, since it provides microorganisms, such as bacteria, moulds and yeast, with water that supports their growth; the higher the water activity, the larger the chance for spoilage. The water activity is defined as the
ratio of water pressure in the material to the water pressure of pure water under the same condition. It specifies the equilibrium relative humidity and the scale for $a_w$ extends from 0 that is completely dry, to 1.0 that is pure water (Food Science Australia, 2005). In general, a water activity below 0.6 is considered to guarantee a stable product with long storage stability and avoid food spoilage (Lowe and Kershaw, 1995).

The water activity of the raw material varied between 0.86 and 0.91 and showed no significant differences between all blends. This might be due to the ingredient matrix of the blends that binds water better the more DDGS is included in the blend.

Increasing the DDGS content from 10 to 50% resulted in a significant increase from 0.02 to 0.18 for $a_w$ of the extrudates. The values for the water activity are all very low and the final product is therefore extremely dry. This can be attributed to the fact that the extrudates were air-dried post extrusion.

**Unit density**

Unit density is another important factor in fish feed and determines the products floatability, which is important for the quality of aquaculture feed (Chevanan et al., 2007d). It is inversely related to the expansion ratio (Ilo et al., 1999).

The values for the unit density of the extrudate blends ranged from 876.34 to 1030.76 kg/m$^3$ and resulted in an increase of 17%. There is a significant increase in unit density of 11% when raising the DDGS content from 10 to 20%. In accordance with the conclusions of Chevanan et al. (2007d) and Kannadhason et al. (2009b), the change in DDGS levels between 20-40% showed no significant effects on the unit density of the extrudates. All extrudates with a DDGS level between 0 and 30% were measured below the density of water with 1000 kg/m$^3$. However, they did not float and sank slowly to the ground of the beaker. This can be traced back to the porous structure of the pellets that might have rapidly absorbed the water and made the pellets sink. Yellow perch are slow feeders (Webster and Lim, 2002). Since they feed on or near the bottom or from open waters of the lake (Pears and Achtenberg, 1920), floatability of the pellets is not mandatory.

**Expansion ratio**

The level of expansion impacts the unit density, fragility and hardness of the extrudates (Rosentrater et al., 2009a). As shown in table 4, the expansion levels were calculated between 1.04-1.10 and showed no significant differences, except for the treatment with 20% DDGS
content. Since the determined values for the expansion were very low, this difference can be neglected.

These results are contradictory to the statement that the expansion ratio is inversely related to the unit density (Ilo et al., 1999). This could be traced back to fact that expansion depends on the flashing of water vapor and the flow properties of molten starch (Mercier et al., 1989). DDGS naturally has low starch content of 4.7-5.9% (Rosentrater and Muthukumarappan, 2006) and high fiber content. Due to the low starch content, the initially high moisture content and the fact that the expansion ratio was only calculated based upon the radial expansion, neglecting the longitudinal and volumetric expansion, a high ER was not expected.

Compressive strength and compressive modulus

Compressive tests give conclusions about pellets’ capacity to resist forces without breaking or deforming.

The values for compressive strength ranged from 3.06 to 4.28 MPa. In the analysis, the blend with 50% DDGS content had the highest compressive strength at 4.28MPa, and was significantly different from the other blends, except to the blend with 30%. This minor higher resistance against forces can be ascribed to the higher moisture content of the pellets containing 50% DDGS compared to the significantly higher MC than the other pellets.

Mazumder et al. (2007) observed increasing forces applied on ready-to-eat corn balls when increasing moisture content from 2% to 10% which is due to the high starch content of corn. Starch in combination with high water content and heat is gelatinized (Avérous and Halley, 2009). DDGS contains less starch due to the preceding fermentation process; this might be why a minor increase in compressive strength was observed when increasing the DDGS content of the blends. All recorded compressive strength values were low and indicated that the pellets had a fragile structure that broke easily. This could be traced back to the low moisture content of the blends and the low starch content of DDGS.

Compressive modulus is a measure of product stiffness. There were no significant differences for the compressive modulus, which may be due to the high standard deviation. The means were determined between 26.28 and 48.78 MPa. During measuring, the recorded data showed a high variance and the modulus varied from 1.2 up to 92.3 MPa. This highly diverging data can be explained by the fact that the extrudates are complex in structure. Their texture is not homogenous and has different sized particles that induce different reactions on the decrease in volume when forces are applied.
Pellet durability index

Durability, another physical quality parameter of feed pellets, is measured by the amount of fines returned from a batch under standardized conditions. The quality of the material of extruded fish feed is a decisive factor for the producer’s and consumer’s economy. During shipping and manufacturing, pellets are subject to breakage and attrition, which induces fines in the feed. Extrudates need to have a high level of resistance to guarantee efficiency of the product and the ease of feeding (Thomas and van der Poel, 1996; Hansen and Storebakken, 2007). No clear pattern of changes in PDI was observed when increasing the DDGS level. Changing the levels of DDGS showed minor changes in PDI. The blend including 10% DDGS was significantly different to all other blends and resulted in a 1.5% higher PDI than the blend without DDGS. In accordance with the results from Chevanan et al. (2007b), who did studies on twin-screw extrusion, an increase of the DDGS content from 20 to 40% did not result in significant changes in extrudates’ durability. The measured values for durability including DDGS varied between 96.31 and 97.63%, indicating high PDI and therefore very good and resistant properties against destructive forces that occur during transportation or storage.

Water stability

Besides the floatability, the product’s stability in water plays a decisive role in fish feed, since it determines the dissolving period and the loss of nutrients of the pellets once they are exposed to water. Physical properties, blend compositions, processing methods and the type of binders used, affect extrudates’ water stability. Furthermore, the duration of extrudates’ water stability depends on the time fish need to consume their ration (Lim and Cuzon, 1994).

The time pellets needed to dissolve in distilled water all lay above 30 min. Only the extrudates without DDGS started dissolving after 29 min. The time pellets needed to dissolve in rotating distilled water were between 14.5 min for the blend without DDGS and between 24 to above 30 min for the extrudates containing DDGS. This resulted in an adequate water stability property for all blends.

Color

Other than for food products, the color of the product generally plays no decisive role for the sales market in aquaculture feed, but it can give conclusions about the damage of lysine in 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 in extrusion cooking (Björck and Asp, 1983). A significant
decrease of 16.2% in brightness L was observed when increasing the DDGS content from 0 to 50%; this indicates a darker sample the lower the L value. The blends without and containing 10% DDGS and the blends with 40 and 50% DDGS content showed no significant difference to one another in brightness.

Regarding the changes in redness, all a values resulted in significant differences; increasing the DDGS content resulted in a steady increase in redness by 32.7%. Similar conclusions for redness and brightness ascertained by Chevanan et al (2007b) for twin-screw extrusion trials including DDGS.

As the DDGS content was raised from 0 to 50% the yellowness b decreased by 11.3%. For the blend containing 30% DDGS b was higher than for the blend containing 20% DDGS. This value is higher than expected and might be attributed to the high value for standard deviation.

DDGS is dark yellow-brown in color; in increase in DDGS content can be expected to result in darker brownish extrudate. Comparing the change in color of the raw material to the extrudates, brightness was decreased from 21.9% to 16.2%, redness was increased from 18.9% to 32.7%, and yellowness was decreased from 1.9% to 11.3%.

As a result, it can be concluded that the changes in color were not only affected by the changes in DDGS content and ingredient composition, but partially due to the processing conditions relating to the Maillard reaction.

**Conclusion**

This study was conducted with the goal of producing feed suitable for juvenile yellow perch by enhancing the amount of DDGS, using a constant feed moisture content (60-65%), constant net protein content (31.5%) and constant extruder parameters. Changing the levels of DDGS had significant effects on the extrudates’ unit density, water activity, color (L, a, b), and on the raw material’s water activity and color (L, a, b). 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 content of the blends. The compressive strength showed low values and fragile characteristics. In contrast, the PDI values were high, resulting in very good extrudates, which were resistant against destructive forces. The combination of low compressive strength and high PDI provides pellets with excellent transport properties, which are easily consumable by the fish. Moreover, results showed very good extrudate water stability; namely, it took at least half an hour before the extrudates would dissolve. All pellets showed significant changes in color after extrusion due to the processing
conditions, and partially due to the composition of the raw materials themselves. In summary, this investigation yielded good quality and high quantity extrudates. Future work should be focused on the acceptability in actual fish diets and resulting growth performance.

Acknowledgements

The authors thank the Agricultural Experiment Station, South Dakota State University, and the North Central Agricultural Research Laboratory, USDA-ARS, Brookings, South Dakota, 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.

References


Table 1: Ingredient components (g/100g) and their compositions (dry basis) of the feed blends.*

<table>
<thead>
<tr>
<th>Ingredients (%) db</th>
<th>Diet 1</th>
<th>Diet 2</th>
<th>Diet 3</th>
<th>Diet 4</th>
<th>Diet 5</th>
<th>Diet 6</th>
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<tbody>
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<td>10</td>
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<td>30</td>
<td>40</td>
<td>50</td>
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<tr>
<td>Soybean meal</td>
<td>31.5</td>
<td>26</td>
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<td>9.5</td>
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<td>24</td>
<td>24</td>
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<td>Vitamin mix</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
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<td>Mineral mix</td>
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<td>8</td>
<td>8</td>
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<tr>
<td>Soybean oil</td>
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<td>4.4</td>
<td>3.3</td>
<td>2.2</td>
<td>1.1</td>
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<tr>
<td>Celufil</td>
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<td>6.8</td>
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<tr>
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<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
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<td>100.0</td>
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<table>
<thead>
<tr>
<th>Feed blend composition</th>
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<tr>
<td>Total moisture (% wb)</td>
</tr>
<tr>
<td>Total dry matter (% wb)</td>
</tr>
<tr>
<td>Protein (% db)</td>
</tr>
<tr>
<td>Fat (% db)</td>
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</table>

*All blends were formulated on a dry basis.
<table>
<thead>
<tr>
<th>Properties</th>
<th>Diet (% DDGS)</th>
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<th>30</th>
<th>40</th>
<th>50</th>
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</thead>
<tbody>
<tr>
<td>MC (% db)</td>
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<td>64.42a</td>
<td>64.43a</td>
<td>58.02b</td>
<td>59.21b</td>
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<td>(0.70)</td>
<td>(0.36)</td>
<td>(0.20)</td>
<td>(0.33)</td>
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<tr>
<td>$a_w$ (-)</td>
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<td>0.91a</td>
<td>0.91a</td>
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<td>0.89c</td>
<td>0.87d</td>
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<td></td>
<td></td>
<td>(0.00)</td>
<td>(0.00)</td>
<td>(0.00)</td>
<td>(0.00)</td>
<td>(0.00)</td>
<td>(0.00)</td>
</tr>
<tr>
<td>$k$ (W/m °C)</td>
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<td>0.11a</td>
<td>0.10a</td>
<td>0.10a</td>
<td>0.10a</td>
<td>0.09a</td>
<td>0.09a</td>
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<tr>
<td></td>
<td></td>
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<td>(0.02)</td>
<td>(0.02)</td>
<td>(0.02)</td>
<td>(0.01)</td>
<td>(0.00)</td>
</tr>
<tr>
<td>$\alpha$ (mm²/s)</td>
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<td>0.11a</td>
<td>0.11a</td>
<td>0.11a</td>
<td>0.11a</td>
<td>0.11a</td>
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<tr>
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<td>(0.01)</td>
<td>(0.01)</td>
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<td>(0.01)</td>
<td>(0.00)</td>
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<td>45.68a</td>
<td>45.15a</td>
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<td>(1.45)</td>
<td>(2.86)</td>
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</tr>
<tr>
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<td>9.56bd</td>
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</tr>
<tr>
<td></td>
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<td>(0.06)</td>
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<tr>
<td>$b$ (-)</td>
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<td>(1.15)</td>
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<td>(0.98)</td>
<td>(0.27)</td>
<td>(0.57)</td>
<td>(0.59)</td>
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</tbody>
</table>

*Means followed by similar letters for a given dependent variable are not significantly different at P<0.05, LSD. Values in parentheses are standard deviation. MC is moisture content, $a_w$ is water activity, $k$ is thermal conductivity, $\alpha$ is thermal diffusivity.
Table 3: Treatment effects on extrusion processing parameters.*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Diet (% DDGS)</th>
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<td>10</td>
<td>20</td>
<td>30</td>
<td>40</td>
<td>50</td>
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<tr>
<td>MFR (g/min)</td>
<td>181.33a</td>
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<td>204.00a</td>
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<td></td>
<td>(11.02)</td>
<td>(23.18)</td>
<td>(2.31)</td>
<td>(28.00)</td>
<td>(25.06)</td>
<td>(7.02)</td>
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<tr>
<td>Set Feed Temp. 40°C (°C)</td>
<td>41.00a</td>
<td>39.30b</td>
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<tr>
<td></td>
<td>(0.00)</td>
<td>(0.82)</td>
<td>(0.52)</td>
<td>(0.42)</td>
<td>(0.70)</td>
<td>(0.00)</td>
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<tr>
<td>Set Transition Temp. 90°C (°C)</td>
<td>90.10a</td>
<td>89.80ab</td>
<td>90.90c</td>
<td>89.80ab</td>
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<tr>
<td></td>
<td>(0.74)</td>
<td>(0.42)</td>
<td>(0.88)</td>
<td>(0.79)</td>
<td>(1.06)</td>
<td>(0.67)</td>
</tr>
<tr>
<td>Set Die Temp. 100°C (°C)</td>
<td>100.00a</td>
<td>92.90</td>
<td>100.00a</td>
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<td></td>
<td>(0.00)</td>
<td>(28.82)</td>
<td>(0.00)</td>
<td>(0.79)</td>
<td>(0.48)</td>
<td>(0.48)</td>
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<tr>
<td>Product Temp. (°C)</td>
<td>67.48a</td>
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<td>63.57b</td>
<td>65.08ab</td>
<td>72.09c</td>
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<tr>
<td></td>
<td>(2.73)</td>
<td>(3.39)</td>
<td>(4.16)</td>
<td>(3.33)</td>
<td>(2.86)</td>
<td>(1.62)</td>
</tr>
</tbody>
</table>

* Means followed by similar letters for a given dependent variable are not significantly different at P<0.05, LSD. Values in parentheses are standard deviation. MFR is mass flow rate, Temp. is temperature.
Table 4: Treatment effects on extrudate physical properties.*

<table>
<thead>
<tr>
<th>Property</th>
<th>Diet (% DDGS)</th>
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<th></th>
<th></th>
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<tr>
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<td>10</td>
<td>20</td>
<td>30</td>
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<td>50</td>
</tr>
<tr>
<td>MC (% db)</td>
<td>1.26</td>
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<td>1.45</td>
<td>1.31</td>
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<td>(0.19)</td>
<td>(0.13)</td>
<td>(0.10)</td>
<td>(0.09)</td>
<td>(0.22)</td>
</tr>
<tr>
<td>a_w (-)</td>
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<td>0.02</td>
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<td>0.04</td>
<td>0.05</td>
<td>0.18</td>
</tr>
<tr>
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<td>(0.00)</td>
<td>(0.00)</td>
<td>(0.00)</td>
<td>(0.00)</td>
<td>(0.00)</td>
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<tr>
<td>UD (kg/m³)</td>
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<td>876.34</td>
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<td>975.75</td>
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<td></td>
<td>(83.88)</td>
<td>(66.39)</td>
<td>(53.86)</td>
<td>(60.29)</td>
<td>(45.56)</td>
<td>(34.93)</td>
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<td>ER (-)</td>
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<td>1.09</td>
<td>1.04</td>
<td>1.07</td>
<td>1.10</td>
<td>1.09</td>
</tr>
<tr>
<td></td>
<td>(0.03)</td>
<td>(0.05)</td>
<td>(0.04)</td>
<td>(0.02)</td>
<td>(0.02)</td>
<td>(0.02)</td>
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<tr>
<td>Compressive strength (MPa)</td>
<td>3.15</td>
<td>3.06</td>
<td>3.36</td>
<td>3.64ab</td>
<td>3.54a</td>
<td>4.28b</td>
</tr>
<tr>
<td></td>
<td>(1.21)</td>
<td>(0.60)</td>
<td>(0.73)</td>
<td>(0.85)</td>
<td>(0.46)</td>
<td>(0.53)</td>
</tr>
<tr>
<td>Compressive modulus (MPa)</td>
<td>28.27</td>
<td>48.78</td>
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<td>41.99a</td>
<td>26.28a</td>
<td>41.48a</td>
</tr>
<tr>
<td></td>
<td>(30.34)</td>
<td>(31.06)</td>
<td>(37.30)</td>
<td>(31.01)</td>
<td>(30.28)</td>
<td>(29.79)</td>
</tr>
<tr>
<td>PDI (%)</td>
<td>96.18</td>
<td>97.63b</td>
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<tr>
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<td>(0.29)</td>
<td>(0.28)</td>
<td>(0.28)</td>
<td>(1.05)</td>
</tr>
<tr>
<td>WS stir (min)</td>
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<td>&gt; 30c</td>
<td>24.00d</td>
<td>27.00b</td>
<td>&gt; 30c</td>
</tr>
<tr>
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<td>(0.00)</td>
<td>(1.41)</td>
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<tr>
<td>WS still (min)</td>
<td>29.50</td>
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<td>&gt; 30</td>
<td>&gt; 30</td>
<td>&gt; 30</td>
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<tr>
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<td>(0.00)</td>
<td>(0.00)</td>
<td>(0.00)</td>
<td>(0.00)</td>
<td>(0.00)</td>
</tr>
<tr>
<td>L (-)</td>
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<td>43.97a</td>
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<tr>
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<td>(0.41)</td>
<td>(0.69)</td>
<td>(0.94)</td>
</tr>
<tr>
<td>a (-)</td>
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<td>7.03b</td>
<td>7.67c</td>
<td>8.02d</td>
<td>8.27e</td>
</tr>
<tr>
<td></td>
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<td>(0.09)</td>
<td>(0.08)</td>
<td>(0.12)</td>
<td>(0.05)</td>
<td>(0.14)</td>
</tr>
<tr>
<td>b (-)</td>
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<td>31.18b</td>
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<td>29.74c</td>
<td>28.67e</td>
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<td>(0.12)</td>
<td>(0.06)</td>
<td>(0.33)</td>
<td>(0.29)</td>
<td>(0.32)</td>
</tr>
</tbody>
</table>

*Means followed by similar letters for a given dependent variable are not significantly different at P<0.05, LSD. Values in parentheses are standard deviation. MC is moisture content, a_w is water activity, UD is unit density, ER is expansion ratio, PDI is pellet durability index, WS is water stability.
Figure 1. Cross sections of the resulting extrudates (magnification of x60).