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June, 2007

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American Society of
Agricultural and Biological Engineers

An ASABE Meeting Presentation

Paper Number: 076213

Physical Properties of Extrudates Containing Distillers Grains Extruded in a Twin Screw Extruder

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**Written for presentation at the
2007 ASABE Annual International Meeting
Sponsored by ASABE
Minneapolis Convention Center
Minneapolis, Minnesota
17 - 20 June 2007**

Abstract. *Extrusion trials were conducted with varying levels of DDGS along with soy flour, corn flour, fish meal, vitamin mix, mineral mix and net protein content adjusted to 28% in a Wenger TX-52 twin screw extruder. The properties of extrudates obtained with experiments conducted in full factorial design with 3 levels of DDGS content, 2 levels of moisture content and 2 levels of screw speed were studied. Increasing the DDGS content from 20% to 60%, resulted in 36.7% decrease in the radial expansion leading to 159%, 61.4% increase in the unit density and bulk density of the extrudates. Increasing the DDGS content resulted in significant increase in the water absorption index (WAI) and significant decrease in the water solubility index (WSI) of the extrudates. Changing the screw speed and moisture content had no effect on the radial expansion ratio, but resulted in significant difference in the bulk density of the extrudates and might be due to longitudinal expansion. Even though changing the moisture content and screw speed had no effect on the WSI of the extrudates, significant difference in the WAI of the extrudates was observed. Color changes in the extrudates was mostly due to color changes in the ingredient components and moisture content of the extrudates and screw speed had least effect on the color of the extrudates.*

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Keywords. Distillers dried grains with solubles, twin screw extrusion, physical properties, aquaculture feed

Introduction

Distiller dried grains with solubles (DDGS), a coproduct of ethanol production, contains high amounts of protein and fiber, and a low amount of starch. It is mostly used as animal feed. The protein conversion efficiency of fish is very high compared to other animals. Hence DDGS has great potential to be used as an alternative protein source for aquaculture feed production. Research carried out by Wu et al (1994,1996) indicated that tilapia fish can be grown with DDGS, which can improve the economic viability of aquaculture farms. Since starch is converted to ethanol during the fermentation process, micronutrients are available in concentrated quantities compared to whole corn. This makes it a better base material for aquaculture feed than whole corn. But the main problems with the production of extruded aquaculture feed with DDGS are its low starch and high fiber content (Chin et al 1989). As the starch content is decreased, expansion obtained during extrusion is reduced, which subsequently affects the physical characteristics of the extrudates. As the fiber content is increased, mechanical strength and pellet durability decrease due to its noninteracting nature with other components in the ingredient mix. Whey, a byproduct of cheese making, has excellent binding properties. Whey has actually been used as a binder for production of aquaculture feed by the pelleting process (Lovell 1988). But inclusion of whey during extrusion processing of cereal foods has been found to decrease expansion, increase unit density, water absorption index, and breaking strength (Martinez-Serna and Villota 1992, Matthey and Hanna 1997). The exact mechanism of interaction of whey with other components is not well understood (Cumming et al 1973).

In aquaculture, floating feeds are preferred to sinking feeds, to prevent over feeding, and it can also lead to improved cleanliness in the pond (Lovell 1988, Chang and Wang 1988). Twin screw extruders have various advantages over single screw extruders for production of floating feeds. Twin screw extruders can handle viscous, oily, sticky or wet ingredients with varying levels of protein, starch, fat, fiber, a wide range of particle sizes, etc., and can achieve wide variations in the extrudate properties (Riaz 2000). The main difference between single screw and twin screw extruders is the transport mechanism (Mercier et al 1989). In single screw extruders, the material is transported due to friction between the screw and the product, as well as the barrel and the product. It is very difficult to achieve the required operating conditions for production of floating feeds from ingredient mixes containing DDGS with low starch content. In twin screw extrusion, the material is transported by 'C' shaped chambers formed by intermeshing screws, and the material is transported positively, irrespective of the friction between the screw, barrel surface and material (Zuilichem and Stolp 1984). Hence the operating conditions can be easily achieved by varying parameters such as screw speed, feeding rate, ingredient moisture content, temperature, etc. Hence it is more appropriate to use twin screw extruders for production of floating feeds from ingredient mixes containing low starch such as DDGS.

Aquaculture feeds typically require 26-50% protein, depending on the species (Lovell 1988), so the formulated ingredient mix will often contain high amount of both starch and protein. During extrusion processing of starch based products, a relatively elastic melt is formed inside the barrel which results in a more expanded and crispy product (Ibanoglu et al 1996; Ilo et al 1996; Alves et al 1999; Thomas et al 1999). During extrusion processing of protein based products, on the other hand, a plastic melt is formed inside the barrel and a more porous and textured product is formed (Singh et al 1991; Gwiazda et al 1987; Sandra and Jose 1993; Harris et al 1988). Extrudate floatability can be achieved by the amount of expansion obtained during extrusion processing. Very little information is available on the effect of ingredient mixes containing high amounts of both starch and protein on expansion and other physical properties

of extrudates by twin screw extrusion. Thus the objective of this study was to examine the effect of varying levels of screw speed, moisture content, and DDGS content (in an ingredient blend containing soy flour, corn flour, Menhaden fish meal, mineral mix, vitamin mix and whey) on the physical properties of extrudates during extrusion processing in a twin screw extruder.

Methods and Materials

Feed blend formulation

Three isocaloric ingredient blends were formulated to approximately 28% protein, with an energy content of approximately 350 kcal/100 g. The ingredients in the feed blends included DDGS, soy flour, corn flour, Menhaden fish meal, whey, vitamin mix and mineral mix (Table 1). DDGS was provided by Dakota Ethanol LLC (Wentworth, SD) and was ground to a particle size of approximately 100 μ m using a laboratory grinder (S500 Disc Mill, Genmills Inc. Clifton, NJ). Corn flour was provided by Cargill Dry Ingredients (Paris, IL), and soy flour was provided by Cargill Soy Protein Solutions (Cedar Rapids, IA). The vitamin mix, mineral mix, fish meal and whey were mixed at 1, 2, 5, and 5%, respectively, on wet weight i.e. as-is basis. The ingredients were mixed in a laboratory scale mixer (N50 Mixer, Hobart Corporation, Troy, OH) for 30 min, and then stored at room temperature for two days until the experiments.

Table 1. Ingredient components in the experimental feed blends

Feed Ingredients	Weight of ingredients (g/100g)		
	Blend I	Blend II	Blend III
DDGS	20	40	60
Soy flour	32.9	24.8	16.5
Corn flour	34.1	22.2	10.5
Fish meal	5	5	5
Whey	5	5	5
Mineral mix	1	1	1
Vitamin mix	2	2	2

Experimental design and extrusion processing

The experiments were conducted in a co-rotating fully-intermeshing self-wiping twin screw extruder (Wenger TX-52, Sabetha, Kansas). The extrusion system had a feed hopper, pre-conditioner, and twin screw extruder. The ingredient blends were metered from the feed hopper into the pre-conditioner, which was fitted with steam injection and water injection ports to condition the ingredients to required temperature and moisture content. The conditioned ingredients were dropped in to the extruder with a feeder speed of 14 rpm and the average feed rate achieved during extrusion trials was 49 kg/hr. The extruder had 52 mm diameter twin screws, and the barrel had a length-to-diameter ratio of 25.5:1. The screw had 25 sections, and the configuration used in our experiments was: 4 conveying screws, 3 shear locks, 1conveying screw, 1conveying screw backward, 3 conveying screws, 1 conveying screw backwards, 4 conveying screws, 1 shear lock, 1 interrupted flight conveying screw, 1 conveying screw, 1 interrupted flight conveying screw, 1 shear lock and at the end 1 final (cone) screw. The two die plates each had circular openings of 3.175 mm diameter. The cutter attached at the end of the die had 3 blades, and the rotational speed was adjusted to 750 rpm to produce pelleted extrudates.

Experiments were conducted using a full factorial design, with three levels of DDGS (20, 40, and 60%), two levels of moisture content (15 and 19%), and two levels of screw speed (350 rpm (36.7 rad/s) and 420 rpm (44.0 rad/s)). The barrel had six temperature zones, from the feeding section to die section, which were maintained at 60, 80, 80, 80, 100, and 110°C throughout the experiments.

Measurement of physical properties

Expansion ratio

Radial expansion ratio was measured as the ratio of diameter of the extrudates to the diameter of the die (Conway and Anderson 1973). The diameter of the six extrudates for each treatment was measured using a digital caliper (Digimatic Series No. 293, Mitutoyo Co., Tokyo, Japan) and the average of six readings was used for analysis.

Moisture content

Moisture content was determined following ASAE Method S352.2 (2004), using a forced-convection laboratory oven (Thelco Precision, Jovan Inc., Winchester, VA) at 103 °C for 72 hr

Pellet durability

Pellet durability was determined per ASAE standard method S269.4 DEC01(2004). Two hundred grams of the extrudates were tumbled inside a pellet durability tester for 10 min and sieved through a No. 6 sieve (3.4 mm). The pellet durability was calculated as:

$$\text{Pellet durability \%} = (\text{Mass of pellets after tumbling} / \text{Mass of pellets before tumbling}) \times 100 \quad (1)$$

True density

The true density of the extrudates was determined with a multi-volume pycnometer (Model No. 1305, Multi-volume helium pycnometer, Micromeritics, Georgia, USA) by the volume displacement method using helium gas (Chang 1988). The extrudates were filled in to 150 cm³ cups and the true volume was measured. The true density was calculated as the ratio of mass of extrudates to the true volume of the extrudates (Mohsenin 1986). Calibration of the equipment was performed with a metal ball provided by the manufacturer.

Unit density

Extrudate samples were cut to 2 cm lengths, weighed on an electronic balance (Model A-250, Denver Instrument Co., Arvada, CO), and measured for diameter using a digital caliper (Digimatic Series No. 293, Mitutoyo Co., Tokyo, Japan). Unit density was calculated as the ratio of the mass of each 2 cm extrudate piece to the calculated volume of that piece (assuming cylindrical shapes for each extrudate sample) (Jamin and Flores 1998).

Bulk Density

Bulk density was measured as the ratio of mass of extrudates to the volume of extrudates using a standard bushel tester (Seedburo equipment and Co., Chicago, IL) following the method prescribed by USDA (1999).

Water absorption index

The water absorption index (WAI) was determined by the method followed by Jones et al (2000). Water absorption index is defined as the mass of gel (g) obtained per mass (g) of solids. To determine the water absorption index, 2.5 g of finely ground sample was suspended in 30 mL of distilled water at 30°C in a 50 mL tarred centrifuge tube. The content was stirred intermittently over a period of 30 min and centrifuged at 3000 x g for 10 min. The supernatant

water was transferred carefully into tarred aluminum cups. The mass of the remaining gel was weighed, and WAI was calculated as the ratio of mass of gel to the mass of sample.

Water Solubility Index

The water solubility index (WSI) was determined as the water soluble fraction in the supernatant expressed as percent of dry sample (Jones et al 2000). The water solubility index was determined from the amount of dried solids recovered by evaporating the supernatant in an oven at 135°C for 2 h.

Color

Color of the extrudates was determined using a spectrophotometer (Portable model CM 2500d, Minolta Corporation, Ramsey, New Jersey, USA) using the Hunterlab color space: L* value quantifies the brightness / darkness of the extrudates, a* value quantifies redness / greenness of the extrudates, and b* value quantifies yellowness / blueness of the samples.

Nutrient Analysis

The extrudates were air dried and protein, fiber, fat, ash content were determined following official Methods 990.03, 978.10, 920.39, 920.48 respectively (AOAC 2003). Nitrogen free extracts (NFE) was determined as the percentage weight of sample after deducting moisture, protein, fat, fiber, and ash content. The protein, fat, ash and NFE were measured in duplicate for all the treatments.

Statistical analysis

Three replications were measured for all properties studied except expansion ratio, where six measurements were taken instead. The data were then analyzed with the Proc GLM procedure to determine the main and interaction effects, and least significant differences (LSD) using SAS V.8 (SAS Institute, Cary, NC) using an α level of 0.05.

Results and Discussion

Changing the levels of DDGS had a significant effect on all the parameters studied. Changing the levels of moisture content also had significant effect on all the properties studied, except for expansion ratio, unit density, true density, and extrudate brightness (L*). Changing the screw speed had a significant effect only on pellet durability, true density, bulk density, and water absorption index. None of the interaction effects were found to be significant for expansion ratio, unit density, or yellowness of extrudates. All the interaction effects were found to be significant for moisture content, pellet durability, and bulk density. The interaction effect of moisture content with screw speed was not found to be significant either (Table 2).

Expansion ratio

The extent of radial expansion obtained during extrusion processing significantly affects the floatability of extrudates (Oliveira et al 1992). In our experiments we found that the extrudates obtained from all the 12 treatment combinations floated for more than 16 hours, and maintained cohesive structure during this time. Changing the levels of DDGS from 20% to 60% had significant effect on the expansion ratio of the extrudates and resulted in 36.7% reduction in the expansion ratio of the extrudates (Table 3). But changing the moisture content of the ingredient mix from 15% to 19%, and the screw speed from 350 rpm to 420 rpm, had no significant effects on the expansion ratio of the extrudates (Table 2). Even though the average expansion ratio achieved in the extrudates containing 60% DDGS was 1.05 only, the extrudates floated. The diameter of the extrudates was measured after air drying the samples at room temperature. The moisture content of the extrudates immediately after extrusion processing was found to be highest for the extrudates containing 60% DDGS. More porous structured

extrudates might have been obtained during extrusion processing in a twin screw extruder containing 60% DDGS, which led to floatability of the extrudates. But during drying, shrinkage might have occurred, resulting reduced expansion ratio of 1.05. Post extrusion shrinkage up to 20% to 50% was observed by Park (1976) using various raw materials. In twin screw extrusion, screw speed is generally believed to have little effect on the extrudate expansion (Martin-Cabrejas et al 1999; Ding et al 2005), and in our experiment also we observed that screw speed had no significant effect on the expansion of the extrudates.

Table 2. Interaction results for DDGS, moisture content (MC) and screw speed (SS) on the physical properties of extrudates (p-values)

	Expansion ratio (-)	Moisture content of extrudate (% wb)	Pellet durability (%)	True density (g/cm ³)	Unit density (g/cm ³)	Bulk density (g/cm ³)	WSI (-)	WAI (%)	Color L* value (-)	Color a* value (-)	Color b* value (-)
DDGS	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
MC	0.370	<0.001	<0.001	0.742	0.578	<0.001	0.003	<0.001	0.512	0.041	0.016
SS	0.339	<0.001	0.295	<0.001	0.242	<0.001	0.536	<0.001	0.196	0.012	0.184
DDGS * MC	0.725	0.005	<0.001	<0.001	0.511	<0.001	<0.001	0.050	<0.001	0.363	0.381
DDGS * SS	0.956	<0.001	<0.001	0.495	0.163	<0.001	0.002	0.007	0.194	0.565	0.265
MC * SS	0.952	<0.001	0.004	0.002	0.989	<0.001	0.355	0.778	<0.001	0.823	0.721
DDGS * MC*SS	0.222	<0.001	0.003	0.007	0.965	<0.001	<0.001	<0.001	0.082	0.340	0.324

Moisture content

The moisture content of extrudates is a very important parameter, and has been found to influence pellet durability, water absorption index, and water solubility index (Rolfe et al 2001). During our experiments, we observed that changing DDGS content and moisture content of the ingredient blend did have a significant effect on the moisture content of the resulting extrudates immediately after extrusion. As expected, changing the screw speed had no significant effect on the moisture content of extrudates. Increasing the DDGS content from 20% to 60%, however, resulted in nearly 100% increase in the moisture content of the extrudates (Table 3). In twin screw extruders, the required processing temperature can be achieved by three means: application of heat through steam during preconditioning and extrusion, by heat developed by shearing action (i.e. friction) and application of heat through electrical heaters in various sections of the barrel. The higher DDGS content in the ingredient blend may have required greater quantities of steam to attain the required temperature at the pre conditioner and barrel, and may have resulted in a higher moisture content of the extrudates. The ingredient moisture content at 15% (wb) resulted in a moisture content of 20.79 % (wb) in the extrudates, while an ingredient moisture content of 19% (wb) resulted in an extrudate moisture content of 23.97% (wb) (Table 3). The higher moisture content observed in the extrudates compared to the raw material was due to the moisture added through steam in the pre conditioner and barrel.

Table 3. Main effects due to DDGS, screw speed (SS) and moisture content (MC) on the physical properties of extrudates⁺

	Expansion ratio (-)	MC of extrudates (%wb)	Pellet durability (%)	True density (g/cm ³)	Unit density (g/cm ³)	Bulk density (g/cm ³)	WSI (%)	WAI (-)	Color L* value (-)	Color a* value (-)	Color b* value (-)
DDGS(%)											
20	1.66 ^a (0.02)	12.54 ^a (1.28)	97.76 ^a (0.45)	1.397 ^a (0.003)	0.235 ^c (0.006)	0.236 ^c (0.006)	15.51 ^c (0.51)	3.73 ^a (0.06)	48.26 ^a (0.58)	10.02 ^b (0.17)	37.61 ^c (0.45)
40	1.36 ^b (0.01)	19.11 ^b (0.90)	97.60 ^a (0.19)	1.383 ^b (0.001)	0.342 ^b (0.003)	0.300 ^b (0.003)	16.32 ^b (0.27)	3.34 ^b (0.03)	38.28 ^b (1.13)	10.48 ^b (0.22)	46.48 ^b (0.96)
60	1.05 ^c (0.01)	25.48 ^a (0.65)	96.85 ^b (0.41)	1.366 ^c (0.001)	0.609 ^a (0.007)	0.381 ^a (0.003)	16.96 ^a (0.28)	2.77 ^c (0.28)	32.91 ^c (0.59)	12.50 ^a (0.33)	52.51 ^a (0.59)
SS (rpm)											
350	1.37 ^a (0.01)	21.90 ^a (1.51)	97.31 ^a (0.40)	1.379 ^b (0.003)	0.407 ^a (0.001)	0.309 ^a (0.001)	16.20 ^a (0.30)	3.34 ^a (0.14)	39.40 ^a (2.17)	11.12 ^a (0.43)	45.85 ^a (1.90)
420	1.35 ^a (0.08)	22.85 ^a (0.85)	97.48 ^a (0.36)	1.385 ^a (0.003)	0.384 ^a (0.001)	0.302 ^b (0.001)	16.32 ^a (0.49)	3.22 ^b (0.11)	40.24 ^a (1.90)	10.89 ^a (0.37)	45.21 ^a (1.97)
MC (%)											
15	1.35 ^a (0.08)	20.79 ^b (0.83)	98.20 ^a (0.34)	1.382 ^a (0.006)	0.389 ^a (0.009)	0.301 ^b (0.010)	16.60 ^a (0.20)	3.35 ^a (0.12)	40.03 ^a (2.16)	11.27 ^a (0.48)	44.60 ^b (1.82)
19	1.37 ^a (0.07)	23.97 ^a (1.37)	96.61 ^b (0.26)	1.382 ^a (0.003)	0.401 ^a (0.011)	0.310 ^a (0.009)	15.92 ^a (0.52)	3.21 ^b (0.13)	39.61 ^a (1.93)	10.73 ^b (0.48)	46.47 ^a (2.02)

⁺Means with different letters in a column within each main effect were significantly different (p<0.05), values inside the parenthesis are standard error

Pellet durability

The mechanical strength of the extrudates is determined by pellet durability, and is a very important quality of feed materials (Rosentrater et al 2005). Mechanical strength of the extrudates depends on extent of heat treatment and relative degree of starch transformation inside the barrel. If the ingredients contain highly transformed materials that do not easily interact, the extrudates become noncohesive, resulting in poor pellet durability (Colonna et al 1989). During our experiments we observed that changing the levels of DDGS and moisture content had significant effects on pellet durability (p<0.05), whereas changing the screw speed had no significant effect on the durability. It was observed that increasing the DDGS content from 20% to 40% did not result in significant changes in the pellet durability. But increasing further from 40% to 60% resulted in a significant decrease in the durability. Even though the durability of the extrudates obtained with twin screw extrusion was very high (95.41 to 99.50%), the reduced pellet durability with 60% DDGS content was probably due to low starch and high fiber contents. Significant effect of moisture content on the mechanical strength of the extrudates has been observed by many researchers with different ingredients (Bandyopadhyay and Rout 2001; Rolfe et al 2001; Shukla et al 2005). In our experiments, changing the moisture content of the ingredients had significant effect on the pellet durability and increasing the moisture content from 15% to 19% resulted in 1.65 % increase in pellet durability.

True density

True density depends on physical attributes of the raw materials such as particle size, density, mechanical properties, rheology of different components (single or in combination), in addition to the process of extrusion itself (Smith 1992). Changing the levels of DDGS had a significant effect on the true density of the extrudates (p<0.05), and increasing the DDGS content from 20% to 60% in the ingredient mix resulted in a 2.2% decrease in the true density (Table 3). In order to attain a net protein content of 28%, various raw material combinations were used, which influenced the changes in the true density of the extrudates. Increasing the screw speed from 350 rpm (36.7 rad/s) to 420 rpm (44.0 rad/s) resulted in a significant increase in the true density of extrudates; this might be due to structural changes occurring in the melt

inside the barrel due to denaturation of protein and gelatinization of limited starch. But, changing the moisture content did not result in significant changes in the true density. Significant interaction between moisture content and DDGS content, and moisture content and screw speed (Table 2) was observed. These interactions might have resulted in little change in the true density of extrudates due to changing the moisture content of the ingredient mix.

Unit density

Unit density of extrudates is directly related to the degree of expansion obtained during extrusion processing (Colonna et al 1989). The highest expansion ratio of 1.66 was observed for extrudates containing 20% DDGS; while the lowest unit density of 0.236 g/cm³ was observed for these extrudates (Table 3). The lowest expansion ratio of 1.05 was observed extrudates containing 60% DDGS, while the highest unit density of 0.609 g/cm³ was observed for these extrudates. Increasing the DDGS content from 20% to 60% resulted in a 159% increase in the unit density of extrudates. Changing the screw speed and moisture content, however, did not result in significant changes in the expansion ratio of the extrudates, and conversely did not result significant changes in the unit density of the extrudates.

Bulk density

Bulk density of the extrudates is affected by the volume of pores formed inside the extrudates due to expansion occurring during extrusion processing and pores formed due to filling the irregular shaped extrudates inside the container. Bulk density is very important because it determines the space required to store the extruded feed materials, both at production sites and on farms. All the three independent factors, namely, level of DDGS, screw speed, and moisture content had significant effects on the bulk density of the extrudates ($p < 0.05$) (Table 2). Increasing the DDGS content from 20% to 60% resulted in a 61.4% increase in bulk density (Table 3). This was expected, because as the DDGS content increased, the expansion ratio decreased, and the extrudates became lighter. Increasing the screw speed from 350 rpm (36.7 rad/s) to 420 rpm (44.0 rad/s) resulted in a 2.3% decrease in bulk density, while increasing the moisture content of the ingredient mix from 15% to 19% resulted in a 3% increase in bulk density (Table 3). Even though no significant difference in the radial expansion of the extrudates were observed by changing the moisture content of the ingredient mix and screw speed, significant differences in the bulk density were observed. There may have been differences in the longitudinal expansion, which in turn may have influenced the bulk density of the extrudates.

Water absorption index and Water solubility index

WAI, a measure of volume occupied by the starch after swelling in excess water, is a portion of starch which maintained integrity during extrusion processing (Mason and Hosenay 1986). WSI, on the other hand, is a measure of the degree of starch conversion during extrusion processing and is an indicator of degradation of molecular components (Kirby et al 1988). In general an increase in WSI corresponds to decrease in the WAI of the extrudates, and has been observed by many authors (Ng et al 1999; Kirby et al 1988). In our experiments, increasing the DDGS level resulted in an increasing trend in WSI, and a decreasing trend in WAI of the extrudates. Changing the levels of DDGS, screw speed, and moisture content had a significant effect on the WAI of the extrudates (Table 2). Increasing the DDGS content from 20% to 60% resulted in 25.7 % decrease in the WAI of the extrudates. Increasing the screw speed from 350 rpm (36.7 rad/s) to 420 rpm (44.0 rad/s) resulted in a 3.6% decrease in WAI of the extrudates, while increasing the moisture content of the ingredient mix from 15% to 19% resulted in a 4.2 % decrease in WAI (Table 3).

The levels of DDGS content resulted in significant changes in the WSI of the extrudates. But changing the screw speed and moisture content of the ingredient mix did not result in significant changes in the WSI of the extrudates (Table 3). The WSI depends on various factors. For example, starch sources from cereal and potato result in different levels of WSI, depending upon the amount of amylase and amylopectin present in the starch. The extent of dextrination occurring in the extrudates due high shear and high temperature also influences the WSI (Mercier and Feillet 1975; Gomez and Aguilera 1984; Govindasamy et al 1995). The interaction between the starch and protein influences the WSI of the extrudates as well (Paton and Spratt 1984). In our experiments, increasing the DDGS content from 20% to 60% resulted in a 9.3 % increase in the WSI. There was no significant changes in the WSI due to changing the moisture content of the ingredient mix and screw speed, however (Table 3).

Color

In extrusion processing, Maillard reactions are the most important factor resulting in the loss of color of extrudates. Even though literature sources did not state that the color is an important factor in aquaculture feed, loss of color is typically an indication of alteration or loss of lysine which is an important amino acid needed in the aquaculture diets. Lysine loss of up to 40% has been observed during extrusion processing, due to high temperature. (Bjorck and Asp 1983). In this study, as DDGS content increased from 20% to 60%, a significant decrease of 31.8% in L* value was observed (Table 3). DDGS is typically dark in color compared to soy flour and corn flour. Due to this, as the DDGS content was increased, the brightness decreased. Increasing the moisture content of the feed ingredient mix from 15% to 19% and screw speed from 350 rpm to 420 rpm did not result significant changes in L* value. Increasing the DDGS content from 20% to 60% resulted in 24.8% increase in redness of extrudates, which might be due to the difference in the color of the raw ingredients used before extrusion. Increasing the moisture content from 15% to 19% resulted in a 5.3 % decrease in the redness of the extrudates, but no significant changes in the a* value was observed by changing the screw speed 350 to 420 rpm. Increasing the DDGS content from 20% to 60% resulted in a 39.6% increase in yellowness of the extrudates. This was expected because DDGS was yellowish in color; increasing the DDGS content thus resulted in significant increase in yellowness of the extrudates. Changing the level of screw speed did not result in significant changes in the yellowness of the extrudates, while changing the moisture content from 15% to 19% resulted in a 4.2 % increase in the yellowness of the extrudates. This indicated that the color changes in the extrudates obtained in twin screw extrusion processing is mostly due to changes in the color of the ingredient mix and due to changes in the moisture content of the ingredient blend.

Treatment combination effects

The effect of DDGS on different properties of extrudates can be well understood through examination of the treatment combination effects (Table 4). As the levels of DDGS content was changed, significant changes in the expansion ratio were observed. However, there was no significant effect on expansion ratio due to screw speed and moisture content of the ingredient blend as DDGS varied. In general, as DDGS content increased, the moisture content of the extrudates increased. The moisture content of the extrudates decreased significantly as the DDGS content was increased, and at particular DDGS levels, both screw speed and moisture content of the ingredient blend had significant effects. Moisture content and screw speed had significant effects on the pellet durability, in addition to the levels of DDGS present in the ingredient mix (Table 4). In general, at lower DDGS levels, bulk density and unit density were lower, but true density was higher. The higher true density at lower DDGS levels might be due to the true density difference between the components in the ingredient mix. In general, water absorption index was found to be higher at lower DDGS levels, but there was no significant effect on water absorption index due to moisture content of the ingredient blend or screw speed

at 20% and 40% DDGS levels. However, at the 60% DDGS level, significant effects due to moisture content of the ingredient blend were observed (Table 4). The color (brightness, redness, and yellowness) of the extrudates was mostly due to color of the ingredient components in the blend, and there was no effect due to either moisture content on screw speed at the 20% and 40% levels. But, at 60% moisture content, changing the moisture content of the ingredient blend resulted in significant effect on the color of the extrudates (Table 4).

Table 4. Treatment combination effects due to DDGS, screw speed, and moisture content (MC) on extrudate properties*

Property	Screw Speed (rpm)	20 % DDGS				40% DDGS				60% DDGS			
		MC 15%		MC 19%		MC 15%		MC 19%		MC 15%		MC 19%	
		Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Expansion ratio (-)	350	1.69 ^a	0.02	1.62 ^a	0.05	1.33 ^b	0.03	1.37 ^b	0.04	1.05 ^c	0.04	1.04 ^c	0.03
	420	1.67 ^a	0.01	1.67 ^a	0.01	1.40 ^b	0.02	1.35 ^b	0.05	1.05 ^c	0.07	1.06 ^c	0.01
Moisture content of extrudates (% wb)	350	19.64 ^g	0.27	18.61 ^h	0.21	20.07 ^g	0.25	23.45 ^e	0.54	22.60 ^f	0.92	27.40 ^c	0.45
	420	22.48 ^f	0.60	29.43 ^a	0.62	15.52 ^j	0.21	17.40 ⁱ	0.21	24.41 ^d	0.31	27.87 ^b	0.32
Pellet durability (%)	350	95.73 ^e	0.58	97.97 ^b	0.26	97.85 ^b	0.49	98.09 ^b	0.09	95.69 ^e	0.46	98.98 ^a	0.29
	420	98.14 ^b	0.39	99.50 ^a	0.01	96.83 ^d	0.47	97.64 ^{bc}	0.69	95.41 ^e	0.20	97.02 ^{cd}	0.43
True density (g/cm ³)	350	0.398 ^b	0.002	1.391 ^c	0.001	1.381 ^{ef}	0.001	1.380 ^f	0.003	1.355 ^h	0.003	1.370 ^g	0.001
	420	1.405 ^a	0.002	1.396 ^b	0.003	1.386 ^d	0.004	1.385 ^{de}	0.004	1.369 ^g	0.002	1.370 ^g	0.001
Unit density (g/cm ³)	350	0.216 ^f	0.023	0.234 ^{ef}	0.018	0.357 ^c	0.042	0.343 ^{cd}	0.005	0.633 ^{ab}	0.155	0.661 ^a	0.093
	420	0.236 ^{ef}	0.015	0.253 ^{def}	0.042	0.347 ^{cd}	0.021	0.321 ^{cde}	0.018	0.550 ^b	0.058	0.593 ^{ab}	0.030
Bulk density (g/cm ³)	350	0.232 ^j	0.001	0.241 ^h	0.001	0.295 ⁱ	0.001	0.308 ^d	0.001	0.384 ^b	0.002	0.391 ^a	0.001
	420	0.214 ^j	0.001	0.254 ^g	0.001	0.300 ^e	0.002	0.297 ^f	0.001	0.384 ^b	0.002	0.367 ^c	0.001
WSI (-)	350	16.69 ^{ab}	0.35	15.35 ^c	0.43	17.05 ^a	0.31	15.10 ^c	0.17	15.59 ^c	0.47	17.41 ^a	1.10
	420	16.98 ^a	0.29	13.02 ^d	1.51	15.91 ^c	0.11	17.22 ^a	0.38	17.40 ^a	0.15	17.44 ^a	0.31
WAI (%)	350	3.78 ^a	0.02	3.85 ^a	0.07	3.38 ^{bc}	0.07	3.39 ^{bc}	0.04	2.98 ^d	0.21	2.59 ^f	0.02
	420	3.77 ^a	0.08	3.44 ^a	0.05	3.33 ^{bc}	0.02	3.26 ^c	0.16	2.78 ^e	0.03	2.74 ^e	0.02
Color L* value (-)	350	49.67 ^a	2.24	47.26 ^a	1.21	41.37 ^b	3.05	37.81 ^b	1.36	31.74 ^d	2.00	33.58 ^c	1.50
	420	47.28 ^a	2.28	48.84 ^a	2.09	39.10 ^b	2.11	39.87 ^b	2.00	31.07 ^d	0.47	33.51 ^c	0.28
Color a* value (-)	350	10.16 ^{ef}	0.45	9.75 ^f	0.99	10.36 ^{def}	0.91	11.09 ^{cde}	0.77	13.75 ^a	1.00	11.63 ^{bcd}	0.63
	420	10.47 ^{def}	0.29	9.73 ^f	0.32	10.13 ^{ef}	0.74	10.36 ^{ef}	0.69	12.80 ^{ab}	1.02	11.85 ^{bc}	0.73
Color b* value (-)	350	37.44 ^e	2.23	37.69 ^e	1.10	45.34 ^d	0.79	49.95 ^{bc}	0.54	52.27 ^{ab}	2.72	52.35 ^{ab}	0.40
	420	37.54 ^e	2.08	37.77 ^e	1.73	44.00 ^d	4.17	46.61 ^{cd}	3.60	50.99 ^{ab}	1.12	54.45 ^a	1.62

*Means with different letters for a particular property were significantly different at $p < 0.05$.

Nutrient content

Increasing the DDGS content from 20 to 60% had no significant effect on the protein content of the extrudates. But increasing the DDGS content from 20 to 60% resulted in 69.3 % increase in the fiber content (Table 5). In the same way, increasing the DDGS content from 20 to 60% resulted in a 493.0 % increase in the fat content of the extrudates. The fiber content and fat content of the DDGS was higher than the corn flour and soy flour and hence, increasing the DDGS content from 20 to 60% resulted in significant increase in the fiber content and fat content of the extrudates. Increasing the DDGS content from 20 to 60% resulted in 7.3% decrease in the nitrogen free extracts (NFE) of the extrudates. During ethanol production most of the starch was converted to ethanol. Due to this, the ingredient mix containing lesser amounts of DDGS had increased quantity of starch. This might resulted in higher amount of NFE for the extrudates with the ingredient mix containing 20% DDGS. Changing the levels of moisture content and screw speed had no significant effect on most of the nutrient components studied in our experiments.

Table 5. Nutrient content of extrudates with different levels of DDGS content (n=2)⁺

DDGS content (%)	Protein (% db)	Fiber (% db)	Fat (% db)	Ash (% db)	NFE (% db)
20	30.53 ^a (0.15)	3.62 ^c (0.38)	1.15 ^c (0.09)	5.93 ^c (0.06)	56.76 ^a (0.39)
40	30.85 ^a (0.14)	4.50 ^b (0.27)	2.98 ^b (0.17)	6.05 ^b (0.45)	55.15 ^b (0.26)
60	30.95 ^a (0.22)	6.13 ^a (0.38)	6.82 ^a (0.15)	6.58 ^a (0.07)	52.60 ^c (0.51)

⁺The values inside the parenthesis are standard error.

Means suffixed with different letters were significantly different at p<0.05.

Correlations

Correlation analysis of the multivariate data provides valuable information about the relationship between the different properties in extrusion studies. Higher correlation between some unexpected variables, and lower correlation between some expected variables can lead to important inferences. The correlation coefficients between different variables studied in our experiments are given in the Table 6. In this study, high correlation between expansion ratio with unit density, bulk density and true density was expected. But the high correlation coefficient between the expansion ratio and color (brightness, redness and yellowness) was unexpected and very interesting information. In another study using DDGS, we observed strong correlation between the density of extrudates and color. Similar result was observed by Rosentrater et al (2005) during extrusion studies with corn masa by-products. Higher the correlation coefficient, there exists a strong linear correlation between the variables. Hence it is possible to develop low cost on line product control methods in extrusion processing with color monitoring. The high correlation coefficient of water absorption index with different densities and color of extrudates was also unexpected and needs further study. Water absorption index is directly related to extent of product transformation occurring inside the barrel and interrelated with viscosity, density etc. The strong linear relationship between density, water absorption index and color showed that it may be possible to develop a better online product monitoring system with combined effect of color and viscosity. The high correlation within the color components (brightness, redness and yellowness) of extrudates was expected. This showed that the color changes during extrusion processing with DDGS is mostly due to color changes in the ingredient blend and color changes due to mailard reaction and other chemical changes is minimum.

Table 6. Correlation coefficients for all multivariate extrudate data⁺

	ER	PD	UD	BD	TD	WAI	WSI	MCE	L*	a*	b*
ER	1										
PD	0.256	1									
UD	-0.899	-0.192	1								
BD	-0.967	-0.238	0.922	1							
TD	0.921	0.307	-0.877	-0.940	1						
WAI	0.922	0.070	-0.862	-0.941	0.819	1					
WSI	-0.446	-0.334	0.365	0.317	-0.239	-0.343	1				
MCE	-0.293	0.341	0.418	0.361	-0.248	-0.489	-0.177	1			
L*	0.886	0.236	-0.817	-0.898	0.857	0.788	-0.305	-0.208	1		
a*	-0.717	-0.400	0.735	0.743	-0.767	-0.612	0.257	0.294	-0.725	1	
b*	-0.921	-0.187	0.811	0.910	-0.861	-0.855	0.365	0.309	-0.908	0.739	1

⁺ The values in bold letters had significant correlation coefficients.

ER – Expansion ratio, PD – Pellet durability, UD – Unit density, BD – Bulk density, TD – True density, WAI – Water absorption index, WSI – Water solubility index, MCE – Moisture content of extrudates, L* - brightness, a* - redness, b* - yellowness.

Conclusion

Extrusion studies were conducted using a twin screw extruder with varying levels of DDGS and other ingredients (including soy flour, corn flour, fish meal, vitamin mix, mineral mix and whey). These blends had a net protein content adjusted to 28%. These experiments were conducted using a full factorial design with 3 levels of DDGS, 2 levels of moisture content, and 2 levels of screw speed. The extrudates obtained from all the treatments floated, which is a key for aquaculture feeds. The properties of the extrudates studied included expansion ratio, final moisture content, pellet durability, true density, unit density, bulk density, WSI, WAI and color. Changing the level of DDGS had significant effects on all the properties studied. Changing the moisture content of the ingredient mix had significant effects on moisture content, pellet durability, bulk density, WSI, WAI and yellowness of extrudates. Changing the screw speed had significant effect on true density, bulk density and WAI of the extrudates. The experiments were carried out in a industrial scale twin screw extruder and results showed that aquaculture feed with comparable quality to a commercial feed can be produced using up to 60% DDGS in a twin screw extruder.

Acknowledgements

We thankfully acknowledge the financial support provided by the Agricultural Experiment Station, South Dakota State University, Brookings, SD and the North Central Agricultural Research Laboratory, USDA-ARS, Brookings, SD for carrying out this project.

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