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ORIGINAL PAPER

Effects of Processing Conditions on Single Screw Extrusion of Feed Ingredients Containing DDGS

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Abstract Distillers dried grains with solubles (DDGS), a feed coproduct from the fuel ethanol industry, has been shown to be a viable potential alternative protein source for aquaculture feeds. To investigate this, three isocaloric (3.5kcal/g) ingredient blends containing 20, 30, and 40% DDGS, with a net protein adjusted to 28% (wet basis, wb), were prepared for use as Nile tilapia feed. Extrusion processing was then conducted using three DDGS contents (20, 30, and 40%, wb), three moisture contents (15, 20, and 25%, wb), three barrel temperature gradients (90–100–100°C, 90–130–130°C, and 90–160–160°C), and five screw speeds (80, 100, 120, 140, and 160rpm) using a single screw laboratory extruder. Several processing parameters, including mass flow rate, net torque required, specific mechanical energy consumption, apparent viscosity, and temperature and pressure of the dough inside the barrel and die, were measured to quantify the extrusion behavior of the DDGS-based blends. For all blends, as the temperature profile increased, mass flow rate exhibited a slight decrease, die pressure decreased, and apparent viscosity exhibited a slight decrease as well. Likewise, the net torque requirement, specific mechanical energy consumption, and apparent viscosity decreased as screw speed increased, but mass flow rate increased. Additionally, as moisture content increased, die pressure decreased. At higher temperatures in the barrel and die, the viscosity of the dough was lower, leading to lower torque and specific mechanical energy requirements. Increasing the DDGS content, on the other hand, resulted in a higher mass flow rate and decreased pressure inside the die. As demonstrated in this study, the selection of suitable temperature and moisture content levels are critical for processing DDGS-based ingredient blends.

Keywords Single screw extrusion · Extrusion conditions · Aquaculture feed · DDGS-based blends · Changes in processing parameters · Response surface modeling

Introduction

Extrusion cooking is a high-temperature short-time process in which a final product is obtained by heating, mixing, shearing, and forcing material through a die (Kokini et al. 1992). The rate and extent of heating, mixing, shearing, and compressing of the materials inside the barrel, and subsequently the die, is strongly related to the properties of the raw materials and process conditions used. Hence, understanding the physical, rheological, and chemical properties of an ingredient melt inside the barrel is very important for product development, process control, final product quality, and scaling up operations (Mercier et al. 1989). Each material exhibits distinct behavior during processing and is often quantified by determining temperature and pressure responses, mass flow, and energy consumption.

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Apparent viscosity is one of the most important rheological properties of dough and is often used for continuous online monitoring of the extrusion process and control of subsequent product characteristics (Chen et al. 1978; Lam and Flores 2003) because it can be an indicator of a dough's behavior, and the changes therein, during processing. The viscosity of dough inside extruders has been studied by many authors. For example, the viscosity of doughs containing wheat, corn, and soybeans were measured using straight tube viscometers (Harper et al. 1971), cylindrical dies of different lengths (Harmann and Harper 1974), capillary dies (Jao et al. 1978), viscoamylographs (Remsen and Clark 1978), and capillary rheometers (Luxenburg et al. 1985) attached to food extruders. Viscosity models have also been developed to depict the relationships between viscosity and other process parameters. All of these methods require separate attachments with additional instrumentation to measure the viscosity of the dough during processing. The concentric cylinder approach, on the other hand, has been found to be a very useful method to determine the apparent viscosity inside the barrel and does not require separate attachments or instrumentation. The barrel is considered the outer cylinder of a viscometer arrangement, and the screw is considered the inner cylinder. This method requires appropriate calibration corrections for flight depth changes and tapered screw geometry, however, for this method to produce reliable data.

In the concentric cylinder method, the apparent viscosity is measured as the ratio of the shear stress at the screw surface to the rate of shear at the screw. The shear stress is calculated based on the torque required to shear the material inside the cylinder. A single screw extruder is essentially a pump that simultaneously transports, mixes, shears, stretches, and shapes the material at elevated pressures and temperatures (Eerikainen and Linko 1989). Hence, the shear stress that is determined, based on the torque required to rotate the extruder screw, is not quite equivalent to shear stress determined from the torque required to rotate the inner cylinder of a concentric cylinder viscometer. However, Rogers (1970), Lo and Moreira (1996), Konkoly (1997), Lam and Flores (2003), and Rosentrater et al. (2005) have successfully studied the viscosity of the doughs inside single screw extruders by utilizing appropriate calibrations to account for these differences.

Distillers dried grains with solubles (DDGS) is a product that contains relatively high quantities of protein and has been shown to be a viable potential alternative protein source for aquaculture feeds (Chin et al. 1989; Wu et al. 1994, 1996). The number of corn ethanol plants, and their processing capacities, has been exponentially increasing in recent years. The beginning of 2008 saw 136 manufacturing plants in the USA with an aggregate production capacity of 7.5 billion gallons per year (28.4 billion liters per year). In addition, 71 plants are currently under construction or expansion and, upon completion, will contribute an additional 5.8 billion gallons per year (22.0 billion liters per year; BBI 2008; RFA 2008). Naturally, this growth in the industry will have a direct impact on the amount of ethanol production, and thus the quantity of byproducts that are generated. In fact, more than 17 million tons of DDGS will be produced this year alone.

Previous laboratory experiments with DDGS have yielded extrudates with physical properties suitable for aquaculture feeds (Chevanan et al. 2005a). However, for consistent large-scale production of aquaculture feeds using this protein source, a more thorough understanding regarding the changes occurring inside the extruder is necessary. To date, however, very little information is available regarding extrusion behavior of doughs containing DDGS.

Thus, the objective of this study was to examine the effects of DDGS level, ingredient moisture content, screw speed, and temperature profile on extrusion processing parameters such as mass flow rate, net torque required, specific mechanical energy consumption, apparent viscosity, and temperature and pressure of the dough inside the barrel and die of a laboratory-scale single screw extruder.

Materials and Methods

Sample Preparation

Ingredient blends were formulated with 20, 30, and 40% DDGS on a wet basis (wb), along with appropriate quantities of soy flour, corn flour, Menhaden fish meal, vitamin and mineral mix (Table 1) to achieve a net protein of 28% (wb) and an energy content of 3.5kcal/g. Nile tilapia were the target fish species for these feed blends. These levels were similar to those utilized by El-Sayed and Teshima (1992) who investigated tilapia fry. Additionally, these nutrient levels were chosen based on information discussed by Chevanan et al. (2005b) which states that depending upon the age and physiological state of the fish, protein requirements for tilapia can range between 26 and 50%. The DDGS was provided by Dakota Ethanol LLC (Wentworth, SD) and was ground to a particle size of approximately 100µm using a laboratory grinder (S500 Disc mill, Genmills Inc. Clifton, NJ). Corn flour was provided by Cargill Dry Ingredients (Paris, IL), and the soy flour was provided by Cargill Soy Protein Solutions (Cedar Rapids, IA). Vitamin mix, mineral mix (Vitapak, Land O'Lakes Feed, St. Paul, MN), and fish meal (Consumer Supply Distribution Company, Sioux City, IA) were added at 1%, 2%, and 5%, respectively, on an as-is basis. Whey (Bongards Creameries, Perham, MN) was also added to the

Table 1 Ingredient components in feed blends containing 20, 30, and 40% DDGS and the mean proximate composition of each (values in parentheses represent ±standard error)

Feed ingredient	Mass of ingredients (g/100 g)		
	Blend I	Blend II	Blend III
DDGS	20	30	40
Soy flour	32	28	24
Corn flour	35	29	23
Fish meal	5	5	5
Mineral mix	1	1	1
Vitamin mix	2	2	2
Whey	5	5	5
Proximate analysis (n=2 for each blend)			
Protein (% db)	29.35 (0.32)	32.15 (0.04)	31.35 (0.18)
Fiber (% db)	4.15 (0.11)	4.35 (0.11)	4.55 (0.04)
Fat (% db)	4.90 (0.07)	5.50 (0.01)	6.45 (0.10)
Ash (% db)	7.36 (0.12)	7.31 (0.13)	6.97 (0.03)

blends and served as a binding agent. The ingredients, and appropriate quantities of water, were mixed in a laboratory-scale Hobart mixer (Hobart Corporation, Troy, OH) for 10min and then stored overnight at 10 ± 1°C for moisture equilibration. Before extrusion, proximate analysis was conducted on each raw ingredient blend using two replications (n = 2) for each constituent and consisted of protein, which was determined using Method 990.03, fiber, following Method 978.10, and fat, with Method 920.39 (AOAC 2003). Ash was determined using Method 08-01 (AACC 2000).

Experimental Design and Statistical Analysis

The extrusion runs were conducted using a single screw laboratory-scale extruder (Brabender Plasti-Corder, model PL 2000, South Hackensack, NJ). The extruder had a barrel length of 317.5mm, with a length-to-diameter ratio of 20:1. The die assembly had a conical internal section with a length of 101.6mm. A uniform 19.05-mm pitch screw was used in the experiments. The screw had a variable flute depth, with a depth at the feed portion of 19.05mm and near the die of 3.81mm. The compression ratio achieved inside the barrel was 3:1. The speed of the screw and the temperature inside the barrel were controlled by an external computer. The extruder barrel had external band heaters with provisions to control the temperature of the feed and transition zones in the barrel and die sections. The extruder had a 7.5hp motor, which could control the speed of the screw from 0 to 210rpm (22rad/s). The die insert used in the experiments had a diameter of 2.7mm and a length of 13mm (for an L/D of 4.81).

Experiments were conducted using a 3 × 3 × 3 × 5 full factorial design (for a total of 135 treatment combinations): three DDGS contents (20, 30, and 40%, wb), three moisture contents (15, 20, and 25%, wb), three barrel temperature gradients (90–100–100°C, 90–130–130°C, and 90–160–160°C), and five screw speeds [80, 100, 120, 140, and 160rpm (angular velocities of 8.4, 10.5, 12.6, 14.7, and 16.8rad/s)]. These were implemented using a completely randomized design; each of the 135 treatment combinations was extruded once. After a given setting reached steady state, all processing parameters were measured in triplicate (i.e., n = 3), except for torque, which had ten measurements (i.e., n = 10) for each treatment combination during processing, and approximately 1kg of extrudates were collected for each treatment combination. Formal statistical analyses on all collected data were performed via SAS v.9 (SAS Institute, Cary, NC) and Microsoft Excel v. 2003 (Microsoft Corp., Redmond, WA) software, using a type I error rate (α) of 0.05, and included summary statistics and general linear models (to test for differences between processing parameters and to develop regression prediction equations). TableCurve 3D v.4.0.01 (SYSTAT Software, Inc., San Jose, CA) was also used for response surface modeling.

Extrusion Processing Parameters

The temperature of the dough at the end of the barrel was measured with type J thermocouples (Wahl Instruments, Asheville, NC) with a sensing range of 0 to 400°C. The temperature and absolute pressure in the die were simultaneously recorded with a combined thermocouple/pressure transducer (GP50, New York Ltd., Grand Island, NY) with a sensing range of 0 to 68.9MPa. The torque was measured with a torque transducer (Measurement Specialists, Huntsville, AL) with a sensing range of 0 to 390N m. Torque data were collected every 5s in the computer, and the average of at least ten collected torque values were used in the subsequent determination of the extrusion processing parameters. During experiments, extrudate samples were collected every 30s, and the mass flow rate was then determined (g/min) following Rosentrater et al. (2005). Based on the torque and the mass flow rate data, specific mechanical energy (SME) consumption and apparent viscosity were calculated.

SME (J/g) was calculated according to Harper (1981) and Martelli (1983) as:

$$SME = (\Omega \cdot \omega \cdot 60)\Big/ m_{feed} \qquad (1)$$

where Ω is the net torque exerted on the extruder drive (N m), ω is the angular velocity of the screw (rad/s), and m_{feed} is the mass flow rate [g/min, dry basis (db)].

The apparent viscosity of the dough in the extruder (Pa s) was determined by approximating the extruder barrel and screw as a concentric cylinder viscometer arrangement; this was accomplished by incorporating appropriate calibration corrections for this tapered screw geometry following the methods prescribed by the previously discussed studies. As discussed by Rosentrater et al. (2005), apparent viscosity was calculated as the ratio of shear stress (τ_s) at the screw surface (N/m^2) to the shear rate at the screw ($\dot{\gamma}$, 1/s), which were calculated from the following equations:^{s}

$$\tau_s = \Omega \Big/ \left(2 \cdot \pi \cdot (r_{\text{coor}})^2 \cdot L_s\right) = C_{ss}\Omega \tag{2}$$

$$\dot{\gamma}_s = \left(2 \cdot \omega \cdot r_b^2\right) / \left(r_b^2 - \left(r^2_{\text{coor}}\right)\right) = C_{sr}\omega \tag{3}$$

where r_{corr} is the radius correction due to the screw's frustum geometry ($\sqrt{\left(r^2_{\text{eff1}} + r_{\text{eff}\,1} r_{\text{eff}\,2} + r^2_{\text{eff}\,2}\right) \Big/ 3}$, m), r_{eff} is the effective radius, including the screw root radius and half of the flight height (m), Ω is the net torque exerted on the screw (N m), L_s is the screw length in the axial direction (m), ω is the angular velocity of the screw (rad/s), C_{ss} is an empirical correction factor for shear stress (5,675.4 for the geometry used in the experiments), $\dot{\gamma}$ is the shear rate at the screw surface (1/s), r_b is the inner barrel radius (m), and C_{sr} is the empirical correction factor for shear rate (6.31 for the geometry used in this study). These calibration values were previously developed for this extruder and have been reported elsewhere (Lam 1996; Rosentrater et al. 2005). The apparent viscosity of the dough in the extruder was then calculated by taking the ratio of Eq. 2 to Eq. 3 according to Konkoly (1997), Lam and Flores (2003), Lo and Moreira (1996), and Rogers (1970):

$$\eta_{\text{app}} = \frac{\tau_s}{\dot{\gamma}_s} = \left(\frac{C_{\text{ss}}}{C_{\text{sr}}}\right)\left(\frac{\Omega}{\omega}\right) \tag{4}$$

where η_{app} is the apparent viscosity of the dough in the extruder (Pa s).

Results and Discussion

Effect of Screw Speed

Screw speed had a significant effect ($p < 0.01$) on all the extrusion parameters studied in the experiment (Table 2) except for die temperature. As screw speed increased from 80 to 160rpm, the mass flow rate increased by 78.1% overall, with each increase in speed resulting in a respective increase in mass flow (Table 3). This behavior was expected because drag flow in extruders has been shown to be directly proportional to screw speed (Harper 1981), and higher screw speeds generally result in higher mass flow rates. The apparent viscosity at a screw speed of 160rpm was 62.6% less than that at a screw speed of 80rpm, with each increase in speed resulting in a respective decrease in apparent viscosity, indicating that the dough inside the barrel exhibited shear thinning behavior. In parallel with this trend, the torque required decreased as screw speed increased. On the other hand, at lower screw speeds, the torque required was higher but the mass flow

Table 2 Interaction results (p values) for the levels of DDGS, screw speed, moisture content, and temperature profile on the extrusion processing conditions

Source	Mass flow rate (g/min)	Torque (N m)	SME (J/g)	Die pressure (MPa)	Apparent viscosity (Pa s)	Dough temp at barrel (°C)	Dough temp at die (°C)
DDGS	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
SS	<0.01	<0.01	<0.01	0.04	<0.01	<0.01	0.44
MC	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.40
T	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
DDGS × SS	<0.01	0.39	0.40	0.54	0.76	<0.01	0.44
DDGS × MC	<0.01	<0.01	<0.01	0.05	<0.01	0.08	0.40
DDGS × T	<0.01	<0.01	<0.01	<0.01	<0.01	0.09	<0.01
SS × MC	<0.01	<0.01	<0.01	<0.01	<0.01	0.04	0.20
SS × T	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	0.02
MC × T	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.04
DDGS × SS × MC	0.13	<0.01	0.03	<0.01	<0.01	0.31	<0.01
DDGS × SS × T	0.36	<0.01	<0.01	0.05	<0.01	<0.01	0.04
DDGS × MC × T	0.04	<0.01	0.04	0.69	<0.01	0.04	0.26
SS × MC × T	<0.01	<0.01	<0.01	0.12	<0.01	0.07	0.11
DDGS × SS × MC × T	0.14	<0.01	0.05	<0.01	<0.01	0.11	0.10

MC moisture content, *SS* screw speed, *T* temperature profile in the barrel rate was decreased. Specific mechanical energy was not significantly different for all the screw speeds studied, except at a screw speed of 100rpm. At a screw speed of 160rpm, pressure was 9.6% higher compared to the pressure at a screw speed of 100rpm. At higher screw speeds, the velocity of the dough in the barrel increased, which contributed to a higher pressure inside the barrel. There was no particular consistent trend observed between either the screw speed and the temperature of the dough inside the barrel or the screw speed and the temperature of the dough inside the die.

Effect of Temperature Profile

Temperature profile also had a significant effect ($p < 0.01$) on the extrusion processing parameters studied (Table 2). As expected, the apparent viscosity of the dough decreased as temperature increased and was lowest at the highest temperature profile. Additionally, as the temperature profile increased from 100 to 160°C, the pressure decreased from 13.54 to 3.68Mpa (Table 3). Similar trends were observed by Lam and Flores (2003) during extrusion of fish feed blends in a similar single screw extruder. Moreover, the mass flow rate decreased as the temperature profile increased, but the torque required to rotate the screw decreased; these behaviors were probably due to the higher degree of transformation occurring at the higher temperatures, which thus resulted in decreased viscosity inside the barrel. In general, the viscosity of fluid materials decreases with increasing temperature in an Arrhenius fashion, so results of this type would be expected in the resulting dough in the extruder. Because the reduced viscosity facilitated a reduced torque requirement, as the temperature was increased, the specific mechanical energy also decreased. As expected, as the temperature profile increased, the dough temperatures increased concurrently. Increasing the temperature of the transition zone and die section from 100 to 160°C resulted in a 43.2% increase in the temperature of the dough inside the barrel and a 72.4% increase in the temperature of the dough inside the die.

Effect of Moisture Content

Changing the moisture content of the ingredient blends had a significant effect ($p < 0.01$) on the extrusion processing parameters as well (Table 2), except for die temperature. Increasing the moisture content of the ingredient mix from 15 to 20% did not result in significant change in the mass flow rate, but increasing the moisture content from 20 to 25% did result in a significant reduction (of 12.8%). The lowest apparent viscosity was observed at 15% moisture content. As the moisture content was increased to 20%, the apparent viscosity was found to increase, although increasing the moisture content further resulted in a decreased apparent viscosity of the dough. This behavior may be due to competing interactions between moisture content and the

Table 3 Main treatment effects due to extrusion processing conditions (entries are mean values and standard error)

	Mass flow rate (g/min)	SE	Torque (N m)	SE	SME (J/g)	SE	Die pressure (MPa)	SE	Apparent viscosity (Pa s)	SE	Dough temp at barrel (°C)	SE	Dough temp at die (°C)	SE
Screw speed (rpm)														
80	96.2^{e}	1.8	67.8^{a}	4.7	344.7^{ab}	20.0	8.69^{c}	0.1	7297.9^{a}	503.4	124.0^{ab}	2.9	135.3^{ab}	4.0
100	115.1^{b}	1.7	62.9^{b}	4.2	395.4^{a}	21.1	8.91^{c}	0.1	5332.2^{b}	364.4	123.8^{b}	2.8	135.6^{ab}	4.0
120	136.5^{c}	1.6	58.8^{c}	3.2	323.1^{b}	16.8	9.17^{abc}	0.1	4213.8^{c}	203.4	124.5^{ab}	2.4	134.8^{b}	4.0
140	154.3^{b}	2.0	55.8^{c}	3.4	316.9^{b}	18.0	9.38^{ab}	0.1	3430.2^{d}	206.3	124.8^{a}	2.3	136.6^{a}	4.1
160	171.3^{a}	2.2	50.7^{d}	3.0	296.4^{b}	16.7	9.52^{a}	0.1	2725.9^{e}	161.6	124.4^{ab}	2.2	135.8^{ab}	4.2
Temperature profile (°C)														
90–100–100	139.7^{a}	2.8	78.0^{a}	3.4	444.2^{a}	16.8	13.54^{a}	0.1	6179.8^{a}	381.2	102.2^{c}	0.5	99.2^{c}	0.5
90–130–130	137.6^{b}	3.3	62.4^{b}	2.1	338.8^{b}	10.3	10.19^{b}	0.1	4788.5^{b}	216.4	124.4^{b}	0.2	136.6^{b}	0.4
90–160–160	126.8^{c}	3.2	37.2^{c}	1.0	222.9^{c}	6.3	3.68^{c}	0.1	2831.7^{c}	106.5	146.3^{a}	0.4	171.0^{a}	0.5
Moisture content (% wb)														
15	139.1^{a}	2.9	44.8^{c}	2.1	233.7^{b}	8.0	12.80^{a}	0.1	3597.4^{c}	253.8	123.9^{b}	1.9	135.9^{ab}	3.1
20	140.4^{a}	3.3	57.2^{b}	3.5	399.0^{a}	17.3	9.21^{b}	0.1	5929.7^{a}	372.3	125.1^{a}	1.9	136.1^{a}	3.1
25	124.5^{b}	3.1	75.7^{a}	2.1	373.2^{a}	10.5	5.39^{c}	0.1	4272.9^{b}	188.5	123.9^{b}	2.0	134.9^{b}	3.2
DDGS content (%)														
20	128.0^{c}	2.8	57.4^{b}	2.9	328.9^{ab}	14.6	10.58^{a}	0.1	4503.4^{b}	301.6	124.9^{a}	1.9	136.8^{a}	3.1
30	136.1^{b}	3.2	57.0^{b}	2.7	308.9^{b}	12.4	8.97^{b}	0.1	4452.1^{b}	283.5	124.1^{b}	2.0	135.1^{b}	3.2
40	139.9^{a}	3.4	63.2^{a}	3.2	368.1^{a}	16.8	7.85^{c}	0.1	4844.4^{a}	314.1	123.8^{b}	1.9	134.9^{b}	3.1

SE represents±standard error. Means with same subscript for a given process parameter, within a given independent variable, are not significantly different at $p<0.05$.

other independent variables. On the other hand, the torque requirement significantly increased as the moisture content was increased. In fact, increasing the moisture content from 15 to 25% resulted in a 68.9% increase overall in the torque required (Table 3). Thus, the specific mechanical energy was found to be lowest for the 15% moisture content and highest at 20% moisture content. Even though a reduction in SME was observed when the moisture content was increased from 20 to 25%, this difference was not significant. SME depends upon both torque and screw speed. The significant effect of screw speed on the SME resulted in large variation in SME measured at 20 and 25% moisture content, which might have resulted in no significant difference between the moisture levels. The temperature of the dough, both at the barrel and die, was found to be highest at 20% moisture content, but either an increase or a decrease in the moisture content of the ingredient mix resulted in a slight decrease in the temperature of dough at both the barrel and the die.

Effect of DDGS Level

Furthermore, the level of DDGS in the ingredient mix had a significant effect ($p < 0.01$) on all extrusion parameters studied (Table 2) as well. Increasing DDGS content from 20 to 40% resulted in a significant increase (of 9.3%) in the mass flow rate. Increasing DDGS content from 20 to 30% did not result in significant changes in the apparent viscosity of the dough. However, the apparent viscosity of dough containing 40% DDGS was 8.8% higher than the dough containing 30% DDGS. DDGS contains less starch and higher fiber compared to the corn flour and soy flour in the ingredient mix. Hence, increasing the DDGS content changed the chemical composition, and thus the potential functionality of the ingredients in the dough, and may have resulted in the higher apparent viscosity for this treatment level. Increasing the DDGS content from 20 to 30% did not result in a significant increase in the torque requirement. However, increasing the DDGS content further from 30 to 40% did result in a 10.9% greater torque (Table 3). Due to a higher mass flow rate and a higher torque requirement at higher DDGS content, the highest specific mechanical energy consumption (368.1J/g) was observed at 40% DDGS. There was no significant difference between the specific mechanical energy containing 20 and 30% DDGS. Furthermore, increasing the DDGS content resulted in a significant decrease in the die pressure. The pressure was 34.8% less at 40% DDGS compared to that at the 20% DDGS level. The highest dough temperatures at the barrel and die, respectively, were 124.9 and 136.8°C, which occurred at the 20%

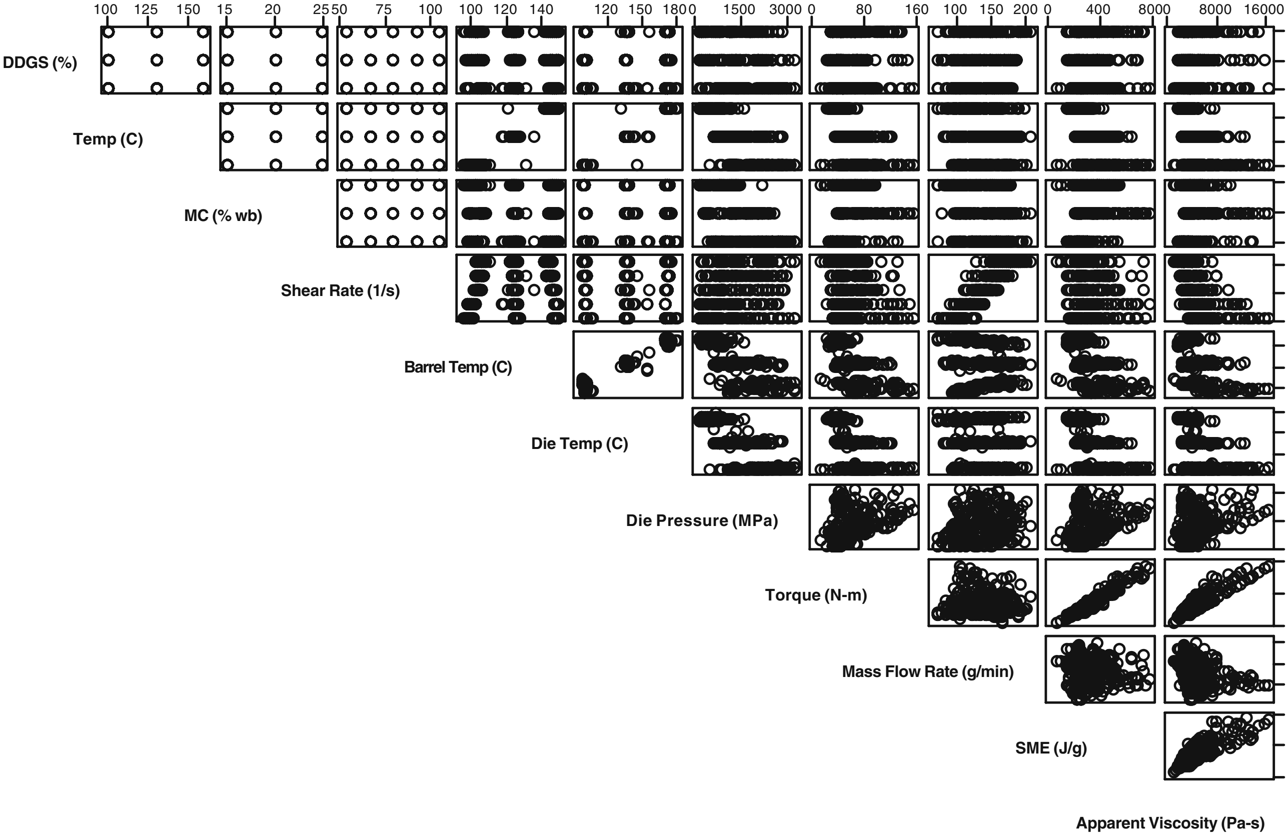

Fig. 1 A scatterplot matrix of all multivariate data collected in the study was used to identify potential relationships between the treatment combinations

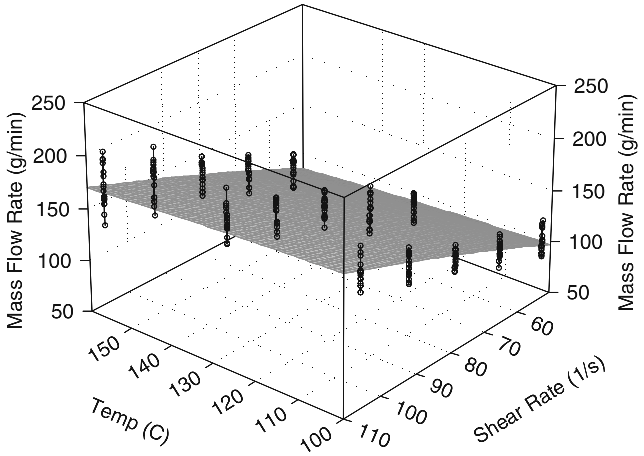

Fig. 2 Response surface relationship between shear rate, barrel temperature, and mass flow rate for all DDGS blends

DDGS level. There was little difference in temperature of the dough at barrel between the ingredient mixes containing 30 and 40% DDGS, however.

Treatment Combination Effects

Not only are the main effects important to consider, but the treatment combination effects and variable interactions (Table 2) are also essential. They delineate where specific trends occur due to the simultaneous alteration of the independent variables, and as shown, many of the interactions were significant. These were visualized through a matrix of bivariate scatterplots (Fig. 1) and several interaction plots (not shown). Some relationships were anticipated due to their relationships via Eqs. 1, 2, 3, 4 (i.e., SME, torque, and apparent viscosity); other relationships were not readily expected. The maximum and minimum mass flow rates achieved with dough containing 20, 30, and 40% DDGS were 174.7 and 84.4g/min, 183.2 and 76.3g/min, 198.4 and 82.4g/min, respectively. At all DDGS levels, as the screw speed (and thus the shear rate) increased, the mass flow rate also increased, which was anticipated a priori. But the mass flow rate decreased as the temperature profile in the barrel was increased. Changing the moisture content of the ingredient blend, on the other hand, did not appear to have any particular effect on mass flow rate. Response surface modeling was then used to examine how the level of shear rate and barrel temperature profile simultaneously affected the mass flow rate through the extruder (Fig. 2) for all blends. The best-fit regression equation (Equation 5 in Table 4) fit the data well and had a fairly high R^2 value of 0.82. The effect of shear rate was linear, but that of temperature was cubic in nature. The temperature effect, although significant, was much smaller than that of shear rate. Similar competing behaviors during extrusion processing have been reported elsewhere (Bouvier et al. 1987; Mercier et al. 1989; Rosentrater et al. 2005).

In general, increasing the temperature profile in the barrel resulted in decreased torque requirement at all DDGS levels. Additionally, at all DDGS levels, the highest torque requirement was observed with the 20% moisture content. Screw speed did not show any particular trend with torque requirement across all DDGS levels. The maximum and minimum torque requirements for the dough containing 20, 30, and 40% DDGS were 140.4 and 27.1N m, 132.8 and 22.9N m, 131.9 and 25.5N m, respectively.

At a barrel temperature of 100°C, the specific mechanical energy required was highest at 20% moisture content compared to 15 and 25% moisture contents across all DDGS levels. But the same trend was not observed at a barrel temperature of 130 or 160°C at all DDGS levels. The maximum and minimum specific mechanical energy requirement for the dough containing 20, 30, and 40% DDGS were 753.3 and 654.9J/g, 165.9 and 142.7J/g, and 635.2 and 141.0J/g, respectively.

For all DDGS levels, increasing the temperature profile in the barrel resulted in reduced pressure developed inside the die. Additionally, as the moisture content of the ingredient blends increased, the pressure developed inside the die decreased as well. However, changing the screw speed did not show any particular trend in the resulting die pressure. The maximum and minimum pressures achieved inside the die containing 20, 30 and 40% DDGS were 20.74 and 1.21MPa, 21.48 and 0.98MPa, 19.39 and 1.03MPa, respectively. From the response surface modeling (Fig. 3), the best-fit regression equation (Equation 6 in Table 4), which quantified how the level of moisture content and barrel temperature affected the resulting die pressure for all blends, fit the data well and had a fairly high R^2 value of 0.83. The

Table 4 Best-fit response surface models for extrusion processing properties for all blends

Equation	Response surface model	R^2	*F* statistic	*p* value	Standard error
5	$\mathrm{MFR} = (31.63) + \left(-4.32 \times 10^{-6}\right)(T^3) + (1.43)(\dot{\gamma}_s)$	0.82	628.6	0.0001	12.7
6	$\mathrm{DP} = (31.75) + \left(-3.21 \times 10^{-6}\right)(T^3) + (-0.74)(\mathrm{MC})$	0.83	637.2	0.0001	2.34
7	$\mathrm{MFR} = (13.16) + (0.01)(\mathrm{DP}) + (1.42)(\dot{\gamma}_s)$	0.83	637.3	0.0001	12.6
8	$\eta_{\mathrm{app}} = (1685.19) + (-0.04)(T^2)\ln(T) + \left(4.80 \times 10^5\right) \Big/ (\dot{\gamma}_s)$	0.57	176.0	0.0001	1,865.9

MFR mass flow rate, *T* barrel temperature, $\dot{\gamma}_s$ shear rate, *DP* die pressure, *MC* moisture content, η_{app} apparent viscosity

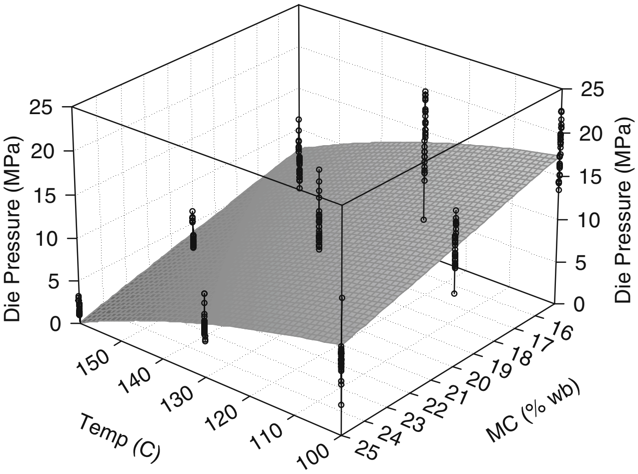

Fig. 3 Response surface relationship between barrel temperature, ingredient moisture content, and die pressure for all DDGS blends

temperature effect, although significant, was considerably smaller than that of moisture content. The effect of moisture content was linear, but that of temperature was cubic in nature. Changing the screw speed affected the rate of mass flow through the extruder, which was related to the resulting die pressure (Fig. 4). The best-fit regression equation for this relationship (Equation 7 in Table 4) also had a high R^2 of 0.83. The effects of both die pressure and shear rate on mass flow was linear in nature. Although the effect of shear rate, and thus screw speed, on mass flow was greater, die pressure also had an effect, which arose from a synergistic combination of DDGS level, moisture content, and temperature. As each of these increased, the resulting die pressure decreased, and a slight decline in mass flow rate was evident.

In general, the apparent viscosity decreased as the screw speed and the temperature profile in the barrel increased. Regarding moisture, the highest viscosity was observed at a moisture content of 20%, and increasing or decreasing the moisture content from this level resulted in reduced apparent viscosity of the dough at all DDGS levels. The maximum and minimum apparent viscosities of the dough containing 20, 30, and 40% DDGS were 14,668.5 and 1,408.9Pa s, 14,288 and 1,229.8Pa s, 14,193.0 and 1,434.3Pa s, respectively. From the response surface modeling (Fig. 5), the best-fit regression equation (Equation 8 in Table 4), which quantified how the level of shear rate and barrel temperature affected the resulting apparent viscosity for all blends, fit the data moderately well and had an R^2 value of 0.57. This occurred because a fair amount of variability was present in the viscosity data. As shown in Fig. 5, the effect of both shear rate and temperature was nonlinear in nature. Many feed and food doughs are pseudoplastic in nature and exhibit a decrease in apparent viscosity when subjected to an increase in applied shear rate (Mercier et al. 1989). Furthermore, viscosity typically decreases as processing temperature increases (Chen et al. 1978; Kokini et al. 1992). These behaviors occur due to structural changes in the food dough (i.e., unfolding of molecules and material structures) during processing (Harmann and Harper 1974; Jao et al. 1978; Luxenburg et al. 1985).

Overall, the observed differences in dough temperature both at the barrel and the die due to changing the screw speed were more pronounced compared to changing the moisture content of the ingredient blends. As expected, increasing the temperature profile in the barrel resulted in a significant increase in the temperature of the dough at both the barrel and the die for all treatments. The maximum dough temperatures at the barrel and the die containing 20, 30, and 40% DDGS were 149.1 and 179.6°C, 149.4 and 173.9°C, and 149.6 and 173.9°C, respectively. The minimum dough temperatures at the barrel and the die for 20, 30, and 40% DDGS were 96.8 and 96.4°C, 96.7 and 97.3°C, and 95.2 and 97.7°C, respectively.

In addition to examining the treatment combination effects, it is also beneficial to consider the composition of

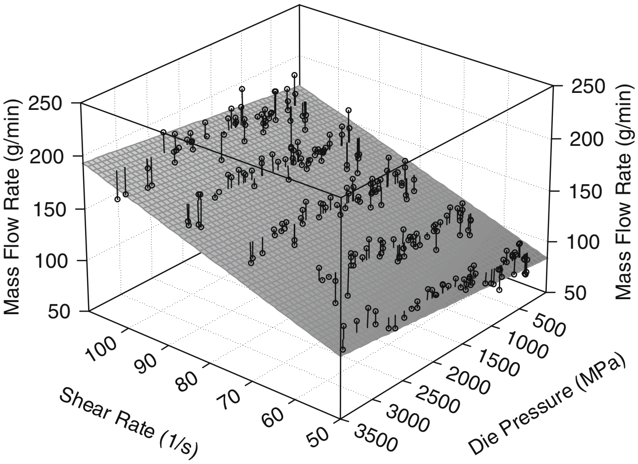

Fig. 4 Response surface relationship between die pressure, shear rate, and mass flow rate for all DDGS blends

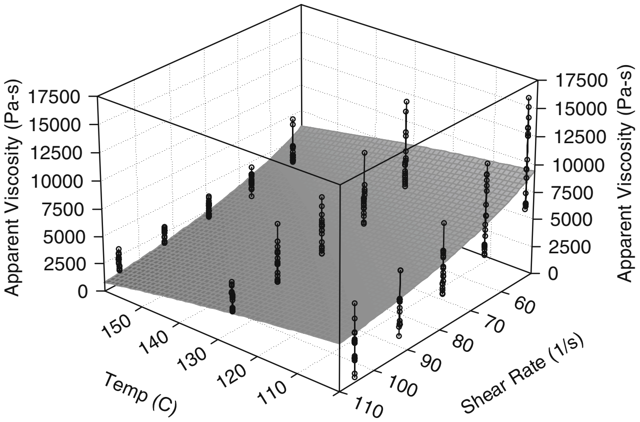

Fig. 5 Response surface relationship between barrel temperature, shear rate, and apparent viscosity for all DDGS blends

the feed blends (Table 1). The average protein content of these blends was 31.4% (db); there was no significant difference in protein content between them. But, the blend containing 40% DDGS did have 31.6% higher fiber content, 65.4% higher fat content, and 13.7% higher ash content compared to the blend containing only 20% DDGS. Increasing the DDGS content in the blend resulted in a decreased starch content, which led to a reduced level of gelanitinized starch inside the barrel during processing. It also led to a higher fiber content. These differences in chemical constituents when the DDGS content in the ingredient blend was increased from 20 to 40% contributed to the competing and interacting effects between the various extrusion processing parameters, and warrants further investigation.

Conclusions

Aquaculture feed mixes used in this study exhibited shear thinning behavior for blends containing DDGS up to 40%. Increasing the DDGS content resulted in a higher mass flow rate and a decreased die pressure. The torque requirement for the ingredient mix containing 40% DDGS was high, which led to a high specific mechanical energy and apparent viscosity of the dough. The torque, specific mechanical energy, and apparent viscosity decreased as screw speed increased. At higher temperatures in the barrel and the die, the viscosity of the dough decreased, which led to a decreased torque requirement and specific mechanical energy. Increasing the moisture content of the ingredient mix did appear to affect the extruder parameters as well. Follow-up studies should examine extrusion processing of DDGS-based ingredients in more detail and should aim to quantify the effect of processing parameters on resulting extrudate properties.

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