Original paper

Effect of Extrusion-Cooking Variables on the Properties of Cornstarch with Soybean Oil

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Cornstarch was extruded using various feed moistures and screw speeds with and without soybean oil. We investigated the effects of each variable and interactions between variables on extrudate characteristics. In starch, the positive linear effect of screw speed and the negative effect of the interaction between moisture and screw speed were significant factors in the degree of gelatinization (DG). The positive linear effect of feed moisture and screw speed and their negative interaction were significant factors in the oil-added extrudates. The water absorption index (WAI) of both extrudates was determined by the linear and quadratic effect of feed moisture and the negative interaction between the two variables. In starch, the positive quadratic effect of moisture and screw speed and their negative interaction affected the water solubility index (WSI). In the oil-added extrudates, the negative effect of feed moisture and the negative interaction of screw speed and feed moisture influenced WSI.

Keywords: extrusion cooking, starch-lipid interaction, digestion and absorption of lipids

Introduction

Oil and fat have the highest energy density of the three major nutrients. Newborn infants or elderly persons capable of eating only small quantities require a high-fat diet to obtain sufficient energy; however, digestibility is an important consideration. On the other hand, in developed countries, the prevalence of obesity has increased due to excessive fat consumption. Since reducing the daily intake of fat is of serious concern, decreasing the amount of fat in foods has become an important requirement for food manufacturers. To control the digestibility and absorption of fat, many studies have proposed structured lipids, a fat substitute, as functional foods.

Extrusion cooking is a popular process used by the food industry to produce expanded snack foods, ready-to-eat cereals, and pet foods (De Pilli *et al.*, 2007).

Extrusion cooking is a continuous cooking, mixing, and forming process that is versatile, low-cost, and efficient. It is carried out using

high temperature and short treatment time. During extrusion cooking, raw materials undergo many chemical and structural transformations (e.g., starch gelatinization, protein denaturation, and degradation reactions of vitamins and pigments) (Ilo *et al.*, 1999). Despite the increased use of extrusion, it remains a complicated process requiring ongoing optimization (Ding *et al.*, 2005).

Because extrusion cooking is typically used for starchy foods, previous studies have focused on the effect of cooking variables, such as feed moisture or screw speed, on extrudate properties. Although the effect of lipids on starch during extrusion cooking has been investigated, “lipids” does not refer to triacylglycerols, but to monoacylglycerols, phosphatidylcholines, or emulsifiers. Little information is available on the effect of triacylglycerols on starchy extrudates, and the digestibility of triacylglycerols in extrudates has been minimally studied. The purpose of our research was to investigate the effect of triacylglycerols on the properties of

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starch-based extrudates, aiming to physical control the digestibility of triacylglycerols. In this study, we investigated the effect of two extrusion-cooking variables (feed moisture and screw speed) on the properties of cornstarch with or without soybean oil (degree of gelatinization (DG), water absorption index (WAI), and water solubility index (WSI)) using response-surface methodology.

Materials and Methods

Raw materials Cornstarch was supplied by the Japan Corn Starch Co., Ltd. (Japan). The chemical composition of starch is given in Table 1. Soybean oil was provided by NOF Corporation (Japan). Oil-added raw samples were prepared by mixing soybean oil and cornstarch at a ratio of 13.1:86.9 on a dry-weight basis. This ratio reflects the starch and fat content of a high-fat AIN-93G diet, which contains 8% fat.

Extrusion cooking Extrusion was carried out using a laboratory-scale co-rotating twin screw extruder (TEX30FC-18, 5PW-V; Japan Steel Works, Ltd., Japan). The extruder had a barrel diameter of 30 mm, a length-to-diameter ratio (L/D) of 18.5, and a die diameter of 4 mm. The extruder consisted of a barrel with four independently controlled temperature zones and an extruder inlet. The screw configuration used is presented in Table 2.

The barrel zone temperatures were set constant at 50°C, 60°C, 95°C, and 90°C, sequentially from the inlet. The inlet temperature was not controlled. The added water was 20%, 50% and 70% of the total weight of the raw materials. The extruder screw speed was 50, 100, or 200 rpm. In the case of 70% water content, a speed of 75 rpm instead of 50 rpm was required in order to maintain stable operation. All combinations of the two extrusion variables, i.e., 9 pairs, were assessed.

The raw materials were added to the extruder inlet with a single screw feeder. Water was introduced directly to the extruder inlet using a tubing pump. The feed flow rate ranged from 2.08 to

2.40 kg/h (average of 2.23 kg/h). Under each condition, the motor current value of the screw was recorded when it reached steady state.

The state of an extrudate just ejected from the extruder is depicted in Fig. 1. The extrudate formed long strings under low feed moisture conditions. With increasing moisture, the extrudate form became less defined. The extrudates were frozen at -80°C and freeze-dried at 3 mTorr for 72 h. The final dried samples were observed using a scanning electron microscope (SEM), and were further analysed after being milled to a powder and passed through a 250-μm mesh sieve.

Degree of gelatinization DG was measured using the β-amylase-pullulanase (BAP) method (Kainuma *et al.*, 1981). The milled extrudates with and without alkali treatment were hydrolyzed with BAP. DG was determined using the following equation:

$$\text{DG (\%)} = \frac{R_s - R_b}{R_a - R_b} \times 100 \quad \dots\dots\text{Eq. 1}$$

R_s : reducing sugar of the milled extrudates

R_a : reducing sugar of the milled extrudates with alkali treatment

R_b : reducing sugar of the milled extrudates treated by inactivated BAP

Water absorption index and water solubility index WAI and WSI of extruded products were determined using the method of Fukami *et al.* (2010). The extrudate powder (0.25 g) was placed in a 15-mL tube and 10 mL of distilled water (20°C) was added. The mixture was homogenized at 17500 rpm for 30 s using a homogenizer and kept at room temperature for 15 h. The suspension volume per extrudate weight was expressed as WAI.

$$\text{WAI (mL/g)} = \frac{\text{Volume of suspension}}{\text{Weight of extrudate powder}} \quad \dots\dots\text{Eq. 2}$$

The powder sample (1.0 g) and 25 mL of distilled water (20°C) were placed in a 50-mL tube. The supernatant was freeze-dried after homogenizing at 17500 rpm for 1 min and centrifugation at $5000 \times g$ for 20 min. WSI was calculated using the following

Table 1. Chemical composition of cornstarch (%)

Ash	Fat	Protein	Moisture	Fiber
0.5	0.03	0.3	12.0	0.5

Table 2. Screw profile used for extrusion experiments

Type of screw element	Length (mm)	Pitch (mm)	Direction	Total length (mm)
Full flight screw	30	30	Forward	150
	30	20	Forward	150
	30	15	Forward	30
Kneading disc*	7.5	—	—	30
Full flight screw	30	15	Forward	30
Kneading disc	7.5	7.5	—	30
Full flight screw	30	15	Forward	30
Full flight screw**	15	15	Reverse	15

*: Four disks are fused together at a right angle.

**: This screw has a slit allowing continuous material flow.

Fig. 1. The extrudate upon ejection from the die. The extrudate expands at the moment of ejection.

equation:

$$\text{WSI (\%)} = \frac{\text{Weight of freeze dried supernatant}}{\text{Weight of extrudate powder}} \times 100 \dots \text{Eq. 3}$$

Data analysis Each variable was coded for statistical analysis (Table 3). RSMaker for Excel (referring the cited URL) was used to analyze the data regarding the relationship between extrusion processing independent variables (feed moisture (x_1) and screw speed (x_2)) with respect to the prescribed properties of the extrudates. The experimental results were fitted to a second-order polynomial. This equation was used to develop the plots for the response functions.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{12} x_1 x_2 + \beta_{22} x_2^2 \dots \text{Eq. 4}$$

The coefficients of the polynomial are represented by β_0 (constant term), β_1 and β_2 (linear effect), β_{11} and β_{22} (quadratic effect), and β_{12} (interaction effect). Feed moisture is denoted by x_1 , and screw speed is denoted by x_2 .

Results

Degree of gelatinization DG influences the digestion of starch and starchy foods (Holm *et al.*, 1988). The digestibility of starch may also affect the release rate and amount of oil included in the starch structure. Therefore, DG is an important characteristic in the digestibility of fat as well as starch.

The corresponding regression equations are given in Table 4. The adjusted coefficient of determination (Adj-R^2) of the predicted models of the extrudates with soy oil was 0.778, and that without soy oil was 0.942. In starch extrudates, this model indicated that the positive linear effect of screw speed and the negative effect of the interaction of moisture and screw speed were significant factors of DG. In contrast, the positive linear effect of feed moisture and screw speed and their negative interaction were significant in the oil-added extrudates.

Although the significant terms of regression equations differed between starch extrudates and oil-added starch extrudates, both regression equations predicted that maximum gelatinization would occur at the lowest feed moisture (20%) and the highest screw speed (200 rpm), whereas minimum gelatinization would occur at the lowest feed moisture (20%) and screw speed (50 rpm). Actual

maximum and minimum data were acquired in the predicted conditions (Table 5).

It is reasonable that the lowest feed moisture and screw speed resulted in the lowest DG, because complete gelatinization by heating requires several times more water than starch (Donovan, 1979). Moreover, a higher screw speed would result in wide distribution of water into the starch, and uniform water distribution can lead to global gelatinization.

On the other hand, the highest DG condition seems to contradict that mentioned above. Maximum gelatinization should be accomplished at the highest feed moisture and the highest screw speed. This result may be due to the degradation or dextrinization of starch. In this study, DG was measured based on the amount of maltose produced by enzymatic hydrolysis. This method does not distinguish between maltose from gelatinized starch and that from

Table 3. Code levels for the experiment (response surface) design

Variable	Level					
	-1.5	-1	-0.5	0	1	2
Feed moisture (% of raw material)	20	—	—	50	70	—
Screw speed (rpm)	—	50	75	100	—	200

Table 5. Combination of extrusion variable and extrudate characteristics

feed moisture	screw speed	DG (%)		WAI (mL/g)		WSI (%)	
		starch	oil added	starch	oil added	starch	oil added
-1.5	-1	55.2	47.6	4.9	4.0	2.2	9.2
-1.5	0	77.2	66.0	6.4	4.1	5.1	23.1
-1.5	2	86.2	96.9	7.5	7.1	16.8	31.2
0	-1	69.1	69.8	4.9	4.0	2.5	8.6
0	0	71.4	71.4	4.7	4.1	2.5	10.0
0	2	81.6	79.5	4.4	4.0	2.4	9.0
1	-0.5	68.8	78.1	8.2	8.9	1.9	7.7
1	0	72.2	79.6	8.9	7.7	1.9	6.5
1	2	76.4	80.3	7.1	6.8	2.2	8.5

Table 4. Significant coefficients derived from regression equations

Response	sample	Model						Adj-R^2	p
		β_0	β_1	β_2	β_{11}	β_{12}	β_{22}		
DG	starch	71.17	—	5.06	—	-2.65	—	0.778	0.005
	oil added	73.15	5.77	5.59	—	-6.54	—	0.942	<0.001
WAI	starch	4.67	1.87	—	1.82	-0.55	—	0.938	<0.001
	oil added	4.03	2.30	—	1.83	-0.74	—	0.952	<0.001
WSI	starch	0.61	—	—	1.97	-2.42	0.90	0.878	0.003
	oil added	11.92	-4.36	—	—	-3.24	—	0.698	0.012

x_1 : Feed moisture. x_2 : Screw speed. Adj-R^2 : Adjusted coefficient of determination.

DG: Degree of gelatinization. WAI: Water absorption index. WSI: Water solubility index.

dextrin. In this method, dextrinization leads to a DG increase, because dextrin has higher amylase sensitivity than raw starch.

Many studies have reported that starch degrades under low moisture and/or high shear conditions (Gomez and Aguilera, 1983 and 1984, Colonna *et al.*, 1984). In the present study, the lowest screw speed did not generate sufficient shear to dextrinize starch and the highest screw speed resulted in dextrinization under the lowest moisture condition.

The maximum DG of soybean oil-added extrudates was higher than that of starch extrudates, whereas the degree of minimum gelatinization of oil-added extrudates was lower.

Both results arose from the prevention of water absorption by oil; the oil interfered with the starch-water contact. Consequently, a further water deficit state was produced and gelatinization was suppressed in the oil-added materials. Also, with a low screw speed, the drop in shear power by the oil also affected DG. The oil on the starch or/and the inner surface of the extruder decreased the friction force between the extrudate and the extruder, resulting in reduced shear. At the lowest and medium moisture levels, the motor current value, which indicated the torque on the screw shaft, actually declined in the oil-added samples compared to the starch samples (Fig. 2.). Thus, little starch degradation occurred, and sufficient water for gelatinization could not be obtained.

With a high screw speed, the same effects as with oil addition were observed. Dextrinization, however, seemed to predominate over gelatinization under a high screw speed condition. Moreover, the prevention of water absorption appeared to affect more strongly the dextrinization than lowering the friction force. Thus, dextrinization was promoted by the addition of oil, and the “dummy” highest DG was acquired.

Although attempts were made to observe the distribution of oil in the extrudates using SEM, suitable images were not obtained (date not shown).

Fig. 2. Motor current value of the screw shaft.

The solid lines show the starch extrudates, and the dotted lines show the oil-added extrudates. The markers show the feed moisture condition: filled diamonds, 20%; filled triangles, 50%; filled square, 70%. Under a 70% feed moisture condition, the starch and the oil added samples have the same current value.

Water absorption index The WAI has generally been attributed to the dispersion of starch in excess water, which increases with the reduction in starch molecular weight (Rayas-Duarte *et al.*, 1998). Molecular weight reduction is caused by gelatinization and extrusion-induced fragmentation.

The relationship between WAI and independent variables obtained from regression analysis is presented in Table 4. In starch extrudates, the Adj- R^2 of the predicted models was 0.938. The predicted model included the linear and quadratic effects of feed moisture and the negative interaction of feed moisture and screw speed. These factors were the same in oil-added extrudates as in starch extrudates, and the Adj- R^2 was 0.952.

Regression analysis indicated that maximum water absorption was achieved through a combination of the highest feed moisture (70%) and the lowest screw speed (50 rpm), regardless of the presence of soy oil.

Minimum water absorption occurred at the lowest screw speed (50 rpm) and lower feed moisture (without oil, 36.7%; with oil, 33.4%).

The actual minimum WAI was obtained with different conditions (Table 5).

Water solubility index WSI is often used as an indicator of the degradation of molecular components (Ding *et al.*, 2005). WSI represents the amount of soluble polysaccharide released from the starch component after extrusion.

Table 4 presents the regression equations generated for WSI with different levels of independent variables. In starch extrudates, the positive quadratic effect of feed moisture and screw speed and their negative interaction effect were included. Adj- R^2 of the model was 0.878.

In the oil-added extrudates, regression analysis yielded the same significant polynomial ($p = 0.012$), for which Adj- R^2 was 0.698. The model indicated the negative effect of feed moisture and the negative interaction of screw speed and feed moisture.

According to this model, maximum WSI is achieved when feed moisture is minimum (20%) and screw speed is maximum (200 rpm) in both extrudates. However, the minimum WSI condition is the medium feed moisture (50%) and screw speed (100 rpm) in starch extrudates, and the highest feed moisture (70%) and screw speed (200 rpm) in oil-added extrudates.

Although each regression equation has different terms, the maximum WSI of both extrudates requires identical conditions. Moreover, these conditions correspond with those of maximum DG. This result agrees with the assumption that a high DG at low feed moisture and high screw speed did not result in true gelatinization, but dextrinization. As mentioned earlier, WSI indicates the amount of soluble polysaccharide and is an indicator of starch degradation. If true gelatinization occurs under this condition, the WSI with the highest feed moisture and screw speed should be approximately equal to that with the lowest moisture and highest screw speed, because that condition resulted in a slightly

lower DG than the lowest moisture and highest screw speed.

However, the condition for minimum WSI is not the same as that for minimum DG. Much gelatinized starch would be produced with this minimum WSI condition. The amount of amylose release at high gelatinization, however, would be lower than the amount of produced dextrin at low feed moisture and screw speed in this experimental condition range. Gomez (1983) also reported on the regression model of WSI that indicated the coefficient of the amount of gelatinized cornstarch was 0.07006 and that of dextrinized cornstarch was 0.84635. Thus, dextrinization had a stronger effect on WSI than gelatinization did.

The condition of actual minimum WSI differs from that estimated by the regression equations (Table 5), because the equations failed the lack-of-fit test. The actual minimum WSI was achieved with the highest feed moisture (70%) and lowest screw speed (75 rpm) in starch extrudates, as well as with the highest moisture (70%) and medium speed (100 rpm).

Discussion

Extrudate characteristics (DG, WAI, and WSI) should relate to each other because they measure and indicate the molecular modification of starch. Gomez and Aguilera (1983) reported that DG correlated strongly with WSI ($r = 0.963$). Altan *et al.* (2009) confirmed that DG correlated with WSI of barley extrudates ($r = 0.788$). Moreover, Badrie and Mellowes (1991) found a negative correlation between WSI and WAI ($r = -0.80$).

In this study, significant correlations between measured extrudate characteristics were not observed, except for between DG and WSI of starch extrudates ($r = 0.594$, $p = 0.045$, Table 6). The significant correlation between DG and WSI seemed to indicate that DG in extrusion cooking could be considered an indicator of the extent of starch degradation rather than an index of gelatinization, as reported by Gomez and Aguilera (1983).

In this study, feed moisture and screw speed were assessed as the extrusion variables. However, other variables, such as barrel temperature, feed rate, and screw configuration, would also affect the extrudate characteristics.

Barrel temperature is an important variable. When the temperature is lower than the gelatinization temperature of the material starch, gelatinization reaction does not occur under high feed moisture. There are a number of reports on the effect of temperature (Meng *et al.*, 2010, Badrie and Mellowes, 1991).

Feed rate is also an important variable, because it determines the staying time and the pressure in the extruder. These condition changes mean changes in the heating time or the shear power on the material. Thus, this variable affects the extrudate characteristics. As mentioned above, the feed rate ranged from 2.08 to 2.40 kg/h in this study. While this difference was unintentional, the feed rate seemed to be approximately constant.

The screw configuration is one of the most complex variables in extrusion cooking. Full flight screws and kneading discs are used

Table 6. Correlation matrix of extrudate characteristics

		DG	WAI	WSI
Starch	DG	1.000		
	WAI	0.215	1.000	
	WSI	0.594*	0.219	1.000
Added oil	DG	1.000		
	WAI	0.582	1.000	
	WSI	0.392	-0.003	1.000

*: Significant at $p < 0.05$

in this study. Full flight screws are used for carrying the materials. As the pitch increases, the carried materials and the inner pressure increase. In the kneading disc, the shear effect is proportional to the thickness of the kneading disc and the fused angle of the each disc. Kneading discs have a carrying property, but in the right angle used in this study. Although only a single combination of the screw elements was tested in this study, further study is needed to examine the effect of screw configuration on the extrudate characteristics.

In the analysis of the digestibility of extrudates, whether the starch of the extrudates is gelatinized or dextrinized is important. If the starch of the extrudate is gelatinized, the gelatinized starch is digested by digestive enzymes, resulting in slow destruction of the extrudate structure. Subsequently, the oil and fat in the gelatinized starch is released; thus, the digestion of the lipids is slow or incomplete. However, if the starch is dextrinized, the oil and fat in the extrudates are released quickly with the dextrin in the gastrointestinal tract before enzymatic hydrolysis of the starch, and are thus digested and absorbed normally.

Starchy extrudates may control lipid absorption or intake by regulating starch gelatinization and dextrinization. More gelatinized extrudates appear to delay and decrease absorption of oil, whereas more dextrinized extrudates may increase fat intake (without a fatty taste) by trapping fat in the starchy structure.

These results indicate the possibility of producing food to control the absorption of oil and fat, by using starch and fat extrudates modified for each purpose. Based on the results of this study, we will examine the effect of starch and oil extrudates on fat absorption in an animal experiment.

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