Food Sci. Biotechnol. Vol. 17, No. 2, pp. 319 ~ 323 (2008)

Food Science and Biotechnology

© The Korean Society of Food Science and Technology

Effects of Moisture and Barrel Temperature of Extrusion Process on Physicochemical and Functional Properties of Specialty Rice Cultivars

Induck Choi[1], Jin Song[2], Choon-Ki Lee[2], Kee-Jong Kim[2], Sea-Jung Suh[2], Jong-Rok Son[3], Gi-Hyung Ryu[4], and Jae-Hyun Kim*

Research and Development Management Division, Rural Development Administration, Suwon, Gyeonggi 441-707, Korea
[1]Department of Food and Nutrition, Sungshin Women's University, Seoul 136-742, Korea
[2]National Institute of Crop Science, Rural Development Administration, Suwon, Gyeonggi 441-857, Korea
[3]Bureau of General Technical Development, Chungnam Agricultural Research and Extension Services, Yesan, Chungnam 365-000, Korea
[4]Department of Food Science and Technology, Kongju National University, Yesan, Chungnam 340-802, Korea

Abstract Mutant rice cv. Goami2 (G2) and Baegjinjoo (BJJ) derived from a high-quality japonica rice cv. Ilpumbyeo (IP) were extruded under different feed moisture (20 and 30%) and barrel temperature (90, 110, and 130°C). Increasing feed moisture at fixed barrel temperature increased extrudate density (ED) in IP and BJJ. Whereas, G2 showed a varied ED depending on extrusion conditions; increasing barrel temperature decreased the ED of G2 extrudate with low feed moisture, but increased with high moisture. Results indicated a positive barrel temperature effect on volume expansion in IP and G2, but a negative effect on BJJ, probably due to shrinkage of expanded products containing low-amylose contents. A significant increase of water absorption was found in G2 and BJJ extruded flour, while an increase of water solubility in those from IP. Non-digestible carbohydrates measured by total dietary fiber (TDF) indicated that extrusion increased slightly TDF in IP and BJJ extrudates, but decreased in G2 products, which might be variety-dependent.

Keywords: specialty rice, extrusion, non-digestible carbohydrate, physical property, functional property

Introduction

Rice is the most important cereal crop and the staple food of over half the world's population. As the primary dietary source of carbohydrates in these populations, rice plays an important role in meeting energy requirement and nutrient intake (1). Starch contains a large digestible portion (digestible starch, DS) and a small non-digestible portion called enzymatic resistant starch (RS). The starch fraction including RS slowly absorbed and digested in the small intestine, resulting in favorable for the dietary management of metabolic disorders such as diabetes and hyperlipidemia (2). In recent, breeding for rice high in RS is of particular interest on regarding to the treatment of non-insulin-dependent diabetes, as it will be easily incorporated into the dietary-prevention strategy (1). A high-quality japonica rice cv. Ilpumbyeo was treated with N-methyl-N-nitrosourea (MNU), resulting in the development of new rice cv. Goami2 and Baegjinjoo, at the National Institute of Crop Science, Rural Development Administration (RDA) in Korea. 'Goami2', identical to rice cv. Suweon 464, has been studied, and reported as G2 rice was high in amylose content, had β-type crystallinity of starch, and had a markedly lower proportion of short chains in the distribution of glucan-chain fraction of debranched starch, all of which would contribute to the unsuitability for ordinary cooked rice (3). Whereas, 'Baegjinjoo' contains lower amylose content of which levels were similar to that of ordinary glutinous rice cultivar (4), and it is also not desirable for the ordinary cooked rice.

It has been shown that extrusion processing of starch based materials result in changes in the functional properties of extruded products, such as water absorption index, water solubility, breaking strength, and rheological behavior of flour slurry (5,6). Guha and Ali (7) suggested that the changes in physical and functional properties of starch foods during extrusion cooking are highly dependent upon the conditions of extrusion and variety of starch sources. Thus, severity of extrusion cooking and the composition of starch in the variety of rice cultivar impart specific properties to the respective starch-based extruded product. A processing efficiency of extrusion for activating ferulic acid, which existed in the walls of rice bran, was demonstrated in the study by Yun *et al.* (8), reporting the usefulness of extrusion as structural modifier for rigid cell wall of cereals when combined with enzymatic treatment. Also, Hwang (9) employed extrusion processing as an effective process for weakening rigid plant cell wall structure.

In the present study, the effects of barrel temperature and feed moisture during extrusion on specialty rice cultivars of 'Ilpumbyeo', 'Goami2', and 'Baegjinjoo' were investigated with the physical and functional properties and the non-digestible carbohydrate components in the extrudate products.

Materials and Methods

Rice plants Rice cv. Goami2, Ilpumbyeo, and Baegjinjoo were grown at the National Institute of Crop Science, RDA, Suwon, Korea during 2005 growing season. Rice paddies were dehusked using a rice sheller (SY88-TH;

*Corresponding author: Tel: +82-31-299-2611; Fax: +82-31-299-2629
E-mail: kjh2000@rda.go.kr
Received July 7, 2007; accepted September 9, 2007

Sangyong Ltd., Incheon, Korea) for brown rice, which was milled using a rice mill (MC-90A; Dongyang Co., Korea). Milled rice was obtained based on 8% bran layer removal from its brown rice. The milled rice was further ground using a grinding mill (Cyclotec™ 1093 sample mill; Foss Tecator Co., Hillerod, Denmark) for extrusion processing.

Extrusion process Rice flour was extruded in a co-rotating twin-screw extruder (THK 31; Incheon Machinery Co., Incheon, Korea) with a 25:1 barrel length to diameter ratio. The extruder was equipped with a circular die of 3.0 mm diameter. Water was injected into the barrel around the feed section to control moisture content from 20 to 30%. Barrel temperature was adjusted from 90 to 130°C with an electric heater and circulated cold water. When the extrusion system reached a steady state as indicated by constant torque, pressure, and temperature, extrudate samples were collected. Screw speed and feed rate were fixed with 200 rpm and 0.9 kg/hr, respectively. All collected samples were oven dried at 50°C to adjust the moisture content to less than 12% before grinding in a laboratory mill followed by passing through a 100 mesh sieve. The ground extrudates were stored in airtight plastic containers and held at room temperature until analysis. A full factorial experimental design was used to show the effects of interactions of feed moisture (20 and 30%) and barrel temperature (90, 110, 130°C) on 3 rice cultivars, which comprised 18 extrusion runs.

Extrudate density and volume expansion Extrudate density (ED) and sectional volume expansion (VE) were calculated as follows (10).

$$\text{Density}=(4\times m)/(\pi\times D^2\times L)$$

Where, m is the mass of a length L of extrudate with diameter D. Sectional expansion, which is the ratio of diameter of extrudate to the diameter of extruder die, was used to express the expansion of extrudate. Eight replicates were measured to determine the average value of density and volume expansion.

Water absorption index (WAI) and water solubility index (WSI) The WAI and WSI values were determined by the method (11) with a slight modification. Rice flour (3.0 g) was dispersed in 30 mL distilled water with heating it in a water bath at 60°C for 1 hr. The dispersion was centrifuged (VS-24 SMTI; Vision Scientific Co., Ltd., Gyeonggi, Korea) at 1,200×g for 15 min. After draining the supernatant carefully, the hydrated residue with the water it retained was weighed for WAI determination. The supernatant was dried at 70°C for 15 hr for WSI determination. The values were determined by the equation below, and the average was determined in triplicate measurements.

WAI (g/g)
=(wt. of water uptake in hydrated residue)/(wt. of rice sample)

WSI (%)
=[(wt. of dissolved solids in supernatant)/(wt. of sample)]×100

Non-digestible carbohydrates analysis Non-digestible carbohydrates were analyzed by total dietary fiber (TDF) content in extruded rice flour samples. The TDF contents were determined according to the AOAC Official Method 991.43, an enzymatic-gravimetric method using MES-Tris buffer using a dietary fiber extraction equipment (Fibertec™ System, Foss Tecator Co.). The average was determined in triplicate measurements.

Statistics Experimental data were analyzed using Statistical Analysis System, SAS software Version 8.01 (SAS Institute Inc., Cary, NC, USA). Mean difference was evaluated by Duncan's multiple comparison tests at 5% significance level.

Results and Discussion

Proximate compositions Milled 'Goami2' (G2) rice showed higher values than 'Ilpumbyeo' (IP) and 'Baegjinjoo' (BJJ) in all of the proximate compositions (Table 1). G2 rice is apparently higher in amylose content compared with other 2 rice cultivars, thus based on amylose content (4), G2, IP, and BJJ were classified as a high (33.96±1.16%), an intermediate (18.63±0.67%), and a low amylose (6.43±0.23%) rice cultivar, respectively.

Extrudate density and volume expansion Table 2 presents the extrudate density (ED) of 3 rice cultivars, showing that various extrusion conditions affected the ED properties, ranging from 0.36 to 1.35 g/cm^3. The extrudates from G2 were varied in ED values depending on the extrusion conditions. At low feed moisture, density decreased with increasing barrel temperature, but at high feed moisture, the extrudate produced at 130°C showed the highest ED value, which was denser than other extrudates. Increasing feed moisture at fixed barrel temperature increased the ED of products extruded from IP and BJJ. Whereas, barrel temperature behaved reversely in the extrudate from IP and BJJ, showing that increasing barrel temperature decreased the ED in IP, but increased in BJJ extrudates. The higher barrel temperature increased the extent of gelatinization and also the content of superheated steam that causes the extrudate to expand more, hence leading to the production of a low density product (7,12), which was found in the normal rice IP extrudate. But, increasing barrel temperature resulted in higher ED in the extrudate from BJJ. It is contrast to the study by Guha and Ali (7), reporting that extrudate density of low-amylose rice decreased with increasing barrel temperature. On the other hand, Anderson and Guraya (13) reported that there was much higher re-

Table 1. Proximate compositions of 3 rice cultivars[1)]

Cultivars	Ash (%)	Protein (%)	Lipid (%)	Fiber (%)
'Ilpumbyeo'	0.10±0.03	6.35±0.02	0.24±0.04	0.32±0.03
'Goami2'	0.18±0.07	7.17±0.02	1.52±0.01	0.69±0.02
'Baegjinjoo'	0.20±0.09	6.07±0.12	0.27±0.07	0.43±0.02

[1)]Amylose contents of 'Impumbyeo', 'Goami2', and 'Baegjinjoo' were 18.63±0.67, 33.96±1.16, and 6.43±0.23%, respectively (4).

Table 2. Means of density and volume expansion of the extrudates from 3 rice cultivars[1)]

		Density (g/cm^3)		Volume expansion	
		20%[2)]	30%	20%	30%
90°C[3)]	G2	0.62 ± 0.07^{a}	0.54 ± 0.06^{cd}	1.64 ± 0.13^{cd}	1.58 ± 0.08^{c}
	IP	0.50 ± 0.04^{bc}	0.55 ± 0.05^{cd}	1.94 ± 0.61^{ab}	1.81 ± 0.10^{b}
	BJJ	0.50 ± 0.04^{bc}	0.57 ± 0.07^{cd}	2.01 ± 0.09^{ab}	1.86 ± 0.16^{ab}
110°C	G2	0.52 ± 0.09^{b}	0.45 ± 0.07^{d}	1.77 ± 0.15^{bc}	1.86 ± 0.17^{ab}
	IP	0.45 ± 0.04^{cd}	0.51 ± 0.05^{d}	2.04 ± 0.10^{a}	1.84 ± 0.12^{ab}
	BJJ	0.49 ± 0.05^{bcd}	0.63 ± 0.09^{bc}	1.88 ± 0.09^{ab}	1.71 ± 0.10^{bc}
130°C	G2	0.36 ± 0.07^{e}	0.69 ± 0.05^{b}	1.91 ± 0.16^{ab}	1.74 ± 0.10^{b}
	IP	0.44 ± 0.04^{d}	0.46 ± 0.08^{d}	2.00 ± 0.11^{ab}	1.98 ± 0.09^{a}
	BJJ	0.65 ± 0.06^{a}	1.35 ± 0.27^{a}	1.50 ± 0.08^{d}	1.77 ± 0.25^{b}

[1)]G2='Goami2', IP='Ilpumbyeo', BJJ='Baegjinjoo'; [a-e]different letters at the same column are significantly different at $p<0.05$.
[2,3)]Moisture contents and barrel temperature, respectively.

aggregation of starch granules in waxy starch after microwave heat treatment than occurred in non-waxy starch. Thus, it is possibly speculated that high temperature during extrusion induced a reassociation of amylopectin branch chains in BJJ, resulting in the production of denser extrudate.

The volume expansion (VE) ranged from 1.50 to 2.04, and was reversely related to extrudate density shown in Table 2. In general, the VE value of extrudates increased with increasing barrel temperature and decreasing feed moisture. Also, it was noticed that reduced density had positive effect on volume expansion, resulting in higher VE values. However, the reduced VE with increasing barrel temperature occurred in the extrudate from BJJ, reflecting its increased density as temperature increased. Studies observed the relationship between barrel temperature and sectional/longitudinal expansion of extrudate reported that increasing barrel temperature resulted in decreasing sectional expansion, but increasing longitudinal expansion (10,14). They explained, in the same studies, that shrinkage of expanded products occurred in the extrudate containing low-amylose contents, resulting in decrement of volume expansion. On the other hand, the VE of G2 extrudate, likewise that of IP, increased with increasing barrel temperature, but showing lower values than those of IP extrudates. As shown in the Table 1, G2 rice flour was high in crude protein and lipid as well as amylose contents. These quality factors may influence the lower VE values in G2 extrudates. A study conducted by Faubion and Hoseney (15) reported that adding protein and lipid in wheat-based extrudates reduced expansion and texture. Thus, it can be explained that higher protein and lipids with higher amylose contents in G2 rice may interfere and affect starch gelatinization of G2 extrudates, influencing volume expansion of the products. Chinnaswamy and Hanna (16) reported an agreeable result that low- and high-amylose extrudates showed lower expansion ratio compared to medium amylose extrudates. They also observed that the differences of viscoelastic and flow properties of melted starch with different amylose contents could alter the expansion properties at different extrusion cooking temperature.

WAI and WSI Three rice cultivars of G2, IP, and BJJ showed an increase of water absorbption index (WAI) in extrudate products compared to that of raw rice flour (Table 3). The means of WAI of raw rice were 1.82, 3.01, and 1.40 g/g for G2, IP, and BJJ, respectively. Increasing barrel temperature increased WAI values of G2 extrudates, but decreased of IP extrudates regardless of moisture contents. The WAI of BJJ varied with the temperature, showing that an increase at 90 and 110°C, but a decrease at 130°C. Based on the reported studies, the increase in WAI with increasing temperature could be explained probably due to the higher proportion of gelatinized starch (17). Whereas, Hagenimana *et al.* (18) reported that the decreased WAI with increasing temperature might be due to an increase in starch degradation. Feed moisture content also affected the WAI changes during extrusion. Increasing feed moisture from 20 to 30% resulted in a decrement of WAI values in G2 extrudates, but an increment in IP extrudates. Whereas the extrudates from BJJ showed slightly complicated

Table 3. Means of water absorption index (WAI), water solubility index (WSI), and total dietary fiber (TDF) of extrudates from 3 rice cultivars[1)]

		WAI (g/g)		WSI (%)		TDF (g/100 g)	
		20%[2)]	30%	20%	30%	20%	30%
90°C[3)]	G2	4.88 ± 0.04^{c}	4.03 ± 0.02^{e}	2.19 ± 0.21^{g}	4.23 ± 0.12^{d}	7.03 ± 0.45^{b}	6.63 ± 0.95^{c}
	IP	4.47 ± 0.16^{d}	6.52 ± 0.14^{a}	9.27 ± 0.01^{b}	5.32 ± 0.11^{d}	2.53 ± 0.29^{d}	3.18 ± 0.68^{d}
	BJJ	4.23 ± 0.20^{d}	3.76 ± 0.24^{e}	11.50 ± 0.53^{a}	16.41 ± 0.62^{a}	2.90 ± 0.26^{cd}	2.93 ± 0.15^{d}
110°C	G2	5.40 ± 0.13^{b}	4.94 ± 0.07^{cd}	2.02 ± 0.11^{g}	2.12 ± 0.05^{e}	6.67 ± 1.39^{b}	8.87 ± 0.85^{a}
	IP	4.15 ± 0.64^{d}	6.28 ± 0.11^{a}	8.45 ± 0.60^{c}	6.66 ± 0.28^{c}	3.65 ± 0.64^{cd}	2.67 ± 0.40^{d}
	BJJ	4.49 ± 0.13^{d}	4.56 ± 0.38^{d}	7.28 ± 0.80^{e}	7.70 ± 0.35^{bc}	3.00 ± 0.50^{cd}	3.03 ± 0.15^{d}
130°C	G2	6.48 ± 0.18^{a}	5.73 ± 0.15^{b}	3.43 ± 0.50^{f}	2.55 ± 0.11^{e}	9.00 ± 0.36^{a}	7.90 ± 0.35^{b}
	IP	4.30 ± 0.15^{c}	4.78 ± 0.06^{d}	8.17 ± 0.65^{de}	6.85 ± 0.12^{c}	3.70 ± 0.17^{c}	3.56 ± 0.12^{d}
	BJJ	4.40 ± 0.24^{d}	5.21 ± 0.37^{c}	8.92 ± 0.28^{c}	8.49 ± 1.68^{b}	2.87 ± 0.21^{cd}	3.20 ± 0.46^{d}

[1)]G2='Goami2', IP='Ilpumbyeo', BJJ='Baegjinjoo'; [a-g]different letters at the same column are significantly different at $p<0.05$; means of WAI, WSI, and TDF of raw G2 rice flour were 1.82 g/g, 2.94%, and 10.58 g/100 g, respectively. Means of WAI, WSI, and TDF of raw IP were 3.01 g/g, 1.45%, and 3.17 g/100 g, respectively. Means of WAI, WSI, and TDF of raw BJJ were 1.40 g/g, 9.64%, and 2.58 g/100 g, respectively.
[2,3)]Moisture contents and barrel temperature, respectively.

system, that increasing moisture decreased WAI values at 90°C barrel temperature, but increased at 110 and 130°C. At the lower feed moisture, the WAI of G2 was higher than that of IP and BJJ regardless of barrel temperature, showing that the highest WAI value in the product with 20% moisture at 130°C barrel temperature. But at high feed moisture (30%), IP had significantly higher WAI at 90 and 110°C. The increased WAI with increasing moisture observed in IP and BJJ (110 and 130°C) may be due to the fact that moisture content, acting as a plasticizer during extrusion cooking, reduces the degradation of starch granule, resulting in an increased capacity for water absorption (18). The WAI measures the amount of water absorbed by starch and can be used as an index of gelatinization (19). The decreased WAI with increasing feed moisture in G2 extrudates suggested that the degree of gelatinization in G2 extrudates was not as much as that of IP and BJJ, which probably was due to the lower swelling power of G2 rice (3,4,20). Ding *et al.* (21) explained that during dough cooking coagulation occurred between protein/lipids and amylose, which would play a restrictive role on starch gelatinization resulting in dextrinizaiton. Thus, it is possible that higher contents of protein, lipid, and amylose in G2 rice as well as the lower swelling power would interfere water easily migrate into the starch structure of G2, thus decreases the degree of gelatinization, resulting in lowering WAI in G2 extrudate.

The BJJ extrudate, in general, showed higher water solubility index (WSI) values followed by IP and G2. The mean values of G2 extrudate was lowered at least 3.0-3.5 folds. The WSI in IP extrudates increased with decreasing feed moisture, which was agreeable with reported results in the research (18,22). Anderson *et al.* (19) reported that increase in WSI, with decrease in moisture, may be attributed to higher degradation of starch. For G2 and BJJ extrudates, increasing feed moisture increased the WSI at 90 and 110°C, but decreased at 130°C, suggesting barrel temperature affected the solubility of degraded starch in high- and low-amylose rice cultivars. The higher WSI in BJJ agreed with the literature, which stated that the WSI of waxy rice was higher than that of non-waxy rice extruded at the same processing conditions (23). A higher WSI in low-amylose rice cultivar than that of high-amylose rice was also reported in Guha and Ali (7). WSI, often used as an indicator of degradation of molecular components, measures the degree of starch conversion during extrusion which is the amount of soluble polysaccharide released from the starch component, attributing sometimes to dextrinization (21,24). Bryant *et al.* (22) suggested that a flour with high WSI and low WAI, such as extruded waxy rice flour would be ideal for use in a drink because of its high solubility. Whereas, a flour with high WAI and low WSI could be used in a product, where the main concern is a high viscosity. Extruded flour of higher water absorbing ability (WAI) can provide the viscosity of such a product.

Non-digestible carbohydrates (NDC) in extruded products NDC contents ranged from 6.67 to 9.00 g/100 g in G2, from 2.53 to 3.70 g/100 g in IP and from 2.90 to 3.20 g/100 g in BJJ. Duncan's multiple comparison indicated no significant difference of TDF between IP and BJJ extrudates regardless of moisture contents, except the slight difference by temperature changes in BJJ with 20% moisture. But, the mean difference among G2 extrudates due to extrusion conditions was indicated from Duncan's analysis. Comparing to TDF in raw rice flour shown in Table 3, extrusion cooking decreased the TDF contents in G2 extrudates, whereas TDF in IP and BJJ extrudates varied depending on barrel temperature and feed moisture. The slight increment of TDF in IP and BJJ extrudates may be attributable to the formation of additional non-digestible components from digestible carbohydrate components. During extrusion, insoluble dietary fiber could be partially transformed into soluble dietary fiber, which increased total dietary fiber contents (25). Increasing non-digestible starch during extrusion of barley was found in the research by Østergård *et al.* (26), reporting that the increased glucan content in fiber fraction of extruded samples indicated the presence of enzymically unavailable starch, which was different from resistant starch. Theander and Westerlund (27) explained that highly reactive anhydro-compounds (i.e., 1,6-anhydro-saccharides) were generated during extrusion cooking and these compounds would react with starch or fragmented starch through transglycosidation reactions resulting in the increment of non-digestible components.

Contrast to IP and BJJ, G2 extrudates showed a reduced TDF by extrusion cooking. Approximately 3.0-3.5 folds higher TDF contents in raw G2 rice compared to that of IP rice has been observed in the previous study (20). Higher amylose contents in G2 rice along with the significantly different starch structure would contribute to higher TDF contents. A report by Muir *et al.* (28) supports the assumption, reporting that starch foods high in amylose contents have higher proportion of resistant starch, which is resistible to amylase hydrolysis. Kim *et al.* (29) examined the starch structure of G2, reporting that while IP consisted entirely of well-separated individual starch granules (ISG), G2 consisted of 2 populations, the large voluminous bodies and the smaller forms, the ISGs, representing compound starch granules (CSGs). The CSGs consisted of thin filaments on the entire granule surface, which might function as a structural barrier, limiting the entrance of water into granules and subsequent absorption. It is possibly supposed that the combination of harsh conditions and low moisture contents during extrusion could cause greater shear fragmentation of starch, thus alter the starch structure of G2. The alteration would result in reduced TDF contents in G2 extrudates. In fact, effects of thermal treatment on the content and physicochemical characteristics of the components resistant to amylolytic enzymes are not clear (30). Different authors have described that cooking does not lead to significant differences in TDF content of foods (31), while other scientist observed an increase or decrease of TDF fractions (32,33).

Feed moisture and barrel temperature during extrusion have a profound effect on extrusion characteristics and product quality of mutant rice cv. Goami2 and Baegjinjoo, and their mother rice cv. Ilpumbyeo. The different starch structure and chemical components of those rice cultivars could be transformed during extrusion process, resulting in changes in the physical and functional properties of extruded products, such as bulk density, volume expansion, water absorption index, and water solubility index. Extrusion cooking increased slightly non-digestible carbohydrate contents in IP and BJJ extrudate, but decreased in G2 extruded products. The changes in non-digestible components profile during extrusion may be primarily due to the cultivar dependence.

Acknowledgments

This study was supported by Post Doctorial Course program of the National Institute of Crop Science, RDA, Korea.

References

1. Yang CZ, Shu XL, Zhang LL, Wang XY, Zhao HJ, Ma CX, Wu DX. Starch properties of mutant rice high in resistant starch. J. Agr. Food Chem. 54: 523-528 (2006)
2. Wolever T, Mehling C. High-carbohydrate-low-glycemic-index dietary advice improves glucose dispersion index in subjects with impaired glucose tolerance. Brit. J. Nutr. 87: 477-487 (2002)
3. Kang HJ, Hwang IK, Kim KS, Choi HC. Comparative structure and physicochemical properties of 'Ilpumbyeo', a high-quality japonica rice, and its mutant, 'Suweon 464'. J. Agr. Food Chem. 51: 6598-6603 (2003)
4. Kang HJ, Seo HS, Hwang IK. Comparison of gelatinization and retrogradation characteristics among endosperm mutant rices derived from 'Ilpumbyeo'. Korean J. Food Sci. Technol. 36: 879-884 (2004)
5. Singh N, Smith AC. A comparison of wheat starch, whole-wheat meal, and oat flour in the extrusion process. J. Food Eng. 34: 15-32 (1997)
6. Singh N, Cairns P, Morris VJ, Smith AC. Physical properties of extruded wheat starch-additive mixtures. Cereal Chem. 75: 325-330 (1998)
7. Guha M, Ali SZ. Extrusion cooking of rice: Effect of amylose content and barrel temperature on product profile. J. Food Process. Pres. 30: 706-716 (2006)
8. Yun JM, Lee HL, Lee SH, Hwang JK. Activation of ferulic acid in rice bran by extrusion and polysaccharidase treatment. Food Sci. Biotechnol. 13: 523-524 (2004)
9. Hwang JK. Production of functional carbohydrates by extrusion reactor. Food Sci. Biotechnol. 10: 455-459 (2001)
10. Alvarez-Martinez L, Kondury KP, Harper JM. A general model for expansion of extruded products. J. Food Sci. 53: 609-615 (1988)
11. Anderson RA. Water absorption and solubility and amylograph characteristics of roll-cooked small grain products. Cereal Chem. 59: 265-271 (1982)
12. Ilo S, Liu Y, Berghofer E. Extrusion cooking of rice flour and amaranth blends. Lebensm.-Wiss. Technol. 32: 79-88 (1999)
13. Anderson AK, Guraya HS. Effects of microwave heat-moisture treatment on properties of waxy and non-waxy rice starches. Food Chem. 97: 318-323 (2006)
14. Fan J, Mitchell JR, Blanshard JM. The effect of sugars on the extrusion of maize grits: I. The role of the glass transition in determining product density and shape. Int. J. Food Sci. Tech. 31: 55-65 (1996)
15. Faubion JM, Hoseney RC. High-temperature short-time extrusion cooking of wheat starch and flour. II. Effect of protein and lipid on extrudate properties. Cereal Chem. 59: 533-537 (1982)
16. Chinnaswamy R, Hanna MA. Relationship between amylose content and extrusion-expansion properties of corn starches. Cereal Chem. 65: 138-143 (1988).
17. Steel CJ, Sgarbieri VC, Jackis MH. Use of extrusion technology to overcome undesirable properties of hard-to-cook dry beans (*Phaseolus vulgaris L.*). J. Agr. Food Chem. 43: 2487-2492 (1995)
18. Hagenimana A, Ding X, Fang T. Evaluation of rice flour modified by extrusion cooking. J. Cereal Sci. 43: 38-46 (2006)
19. Anderson RA, Conway HFM, Pfeiffer VF, Griffin EJ. Gelatinization of corn grits by roll and extrusion cooking. Cereal Sci. Today 14: 4-12 (1969).
20. Choi ID, Son JR, Hong HC, Lee JH, Kim KJ. Indigestible carbohydrates contents and physical properties of 'Goami2' harvested at the maximized milling quality. Food Sci. Biotechnol. 15: 254-259 (2006)
21. Ding QB, Ainsworth P, Tucker G, Marson H. The effect of extrusion conditions on the physicochemical properties and sensory characteristics of rice-based expanded snacks. J. Food Eng. 66: 283-289 (2005)
22. Bryant RJ, Kadan RS, Champagrte ET, Vinyard BT, Boykin D. Functional and digestive characteristics of extruded rice flour. Cereal Chem. 78: 131-137 (2001)
23. Pan BS, Kong MS, Chew HH. Twin-screw extrusion for expanded rice products: Processing parameters and formulation of extrudate propertie. pp. 693-709. In: Food Extrusion Science and Technology. Kokini JL, HoCT, Karwe MV (eds). Marcel Dekker, New York, NY, USA (1992)
24. Colonna P, Tayeb J, Mercier C. Extrusion cooking of starch and starchy products. pp. 281-308. In: Extrusion Cooking. Mercier C, Linko P, Harper JM (eds). American Association of Cereal Chemists Inc., St. Paul, MN, USA (1989)
25. Vasanthan T, Gaosong J, Yeung J, Li J. Dietary fiber profile of barley flour as affected by extrusion cooking. Food Chem. 77: 35-40 (2002)
26. Østergård K, Björck I, Vainionpää J. Effects of extrusion cooking on starch and dietary fiber in barley. Food Chem. 34: 215-227 (1989)
27. Theander O, Westerlund E. Studies on chemical modifications in heat-processed starch and wheat flour. Starch/Stärke 39: 88-93 (1987)
28. Muir JG, Birkett A, Brown I, Jones G, O'Dea K. Food processing and maize variety affects amounts of starch escaping digestion in the small intestine. Am. J. Clin. Nutr. 61: 82-89 (1995)
29. Kim KS, Hwang HG, Kang HJ, Hwang IK, Lee YT, Choi HC. Ultrastructure of individual and compound starch granules in isolation preparation from a high-quality, low-amylose rice, 'Ilpumbyeo', and its mutant, G2, a high-dietary fiber, high-amylose rice. J. Agr. Food Chem. 53: 8745-8751 (2005)
30. Bernal MJ, Periago MJ, Ros G. Effects of processing on dextrin, total starch, dietary fiber, and starch digestibility in infant cereals. J. Food Sci. 67: 1249-1254 (2002)
31. Artz WE, Warren CC, Villota R. Twin-screw extrusion modification of a corn fiber and cornstarch extruded blend. J. Food Sci. 55: 746-754 (1990)
32. Chang MC, Morris C. Effect of heat treatment on chemical analysis of dietary fiber. J. Food Sci. 55: 1647-1650 (1990)
33. Periago MJ, Englyst HNH, Hudson GJ. The influence of thermal processing on the non-starch polysaccharide (NSP) content and *in vitro* digestibility of starch in peas (*Pisum sativum, L.*). Lebensm.-Wiss. Technol. 29: 33-40 (1996)