

# Effects of Gelatinization and Moisture Content of Extruded Starch Pellets on Morphology and Physical Properties of Microwave-Expanded Products

Eun Yong Lee,<sup>1</sup> Kyung Il Lim,<sup>1</sup> Jae-kag Lim,<sup>1</sup> and Seung-Taik Lim,<sup>2,3</sup>

## ABSTRACT

Cereal Chem. 77(6):769–773

Extruded pellets were prepared from normal corn starch using a corotating twin-screw extruder (25:1 L/D ratio, 31 mm diameter screw), and then expanded by heating in a conventional microwave oven for 70 sec. The effects of gelatinization level and moisture content of the extruded pellets on the morphology and physical properties of the microwave-expanded products such as puffing efficiency, expansion bulk volume, and bulk density were investigated. The expanded shape and air cell structure differed according to the degree of gelatinization of the pellets. Maximum puffing efficiency and expansion volume with the pellets containing 11% moisture

were achieved at 52% gelatinization. For this level of gelatinization, starch was extruded at 90°C barrel temperature. In addition, the moisture content of the pellets critically affected the expansion behavior. The maximum puffing efficiency and expansion volume were achieved in a moisture range of 10–13%. For optimum product shape and uniform air cell distribution, the pellets should undergo sudden release of the superheated vapor during the microwave-heating. The expansion by microwave-heating was optimized at ≈50% gelatinization.

Extrusion is a large-scale food processing technique and a standard procedure for the manufacturing of many snack foods (Harper 1989). The major food items prepared by extrusion include direct expanded snacks, corn chips, and third-generation pellets for snacks. The third-generation pellets are usually consumed after expansion by frying in hot oil, puffing in hot air, or microwave heating (Anonymous 1998).

The expansion process of the pellets by frying can be divided into three phases (Anonymous 1998). In the first phase, moisture loss occurs at the periphery of pellets into the oil, and the pellet becomes plastic in texture. In the next phase, moisture inside the pellets turns to steam by the heat. And finally, as the vapor quickly evaporates, the pellets expand. For the expansion, the product should be thoroughly cooked and be elastic enough to have gas-retaining ability for air cells. Case et al (1992) reported that specific bulk volume of the frying-puffed product was increased as the gelatinization level of the pellets increased. They suggested also that the gelatinization level of the pellets could predict texture of the expanded products.

Compared with the hot-oil frying, expansion of the extruded pellets by microwave-heating is a relatively new process. This process has gained the popularity from consumers because the expanded product does not contain fat.

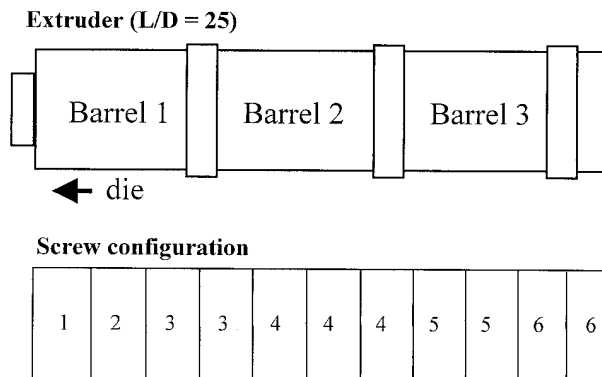
Popping corn is a consecutive process involving buildup of water vapor pressure in individual starch granules, rupture of pericarp by excessive vapor pressure, and then rapid generation and expansion of vapor after the rupture (Hoseney et al 1983, Wu and Schwartzberg 1992). Hoseney et al (1983) found that initial breaks in the pericarp affected popped volume more radically than did subsequent breaks. Through the use of electron microscopy, they reported the starch granules in the translucent endosperm of popcorn were expanded into thin films, whereas those in the opaque part of the endosperm were not expanded at all and retained birefringence. Several studies demonstrated the importance of the integrity and wholesomeness of the pericarp, which acted as a pressure vessel (Hoseney et al 1983, Lin and Ananteswaran 1988). The influence of various physical factors such as moisture content, kernel size, endosperm-to-embryo ratio, and pericarp thickness on the puffing behavior of popcorns

has been examined by many researchers (Metzger et al 1989; Pordesimo et al 1990, 1991; Song et al 1991; Mohamed et al 1993; Song and Eckhoff 1994; Kim et al 1995).

With the increasing popularity of microwave ovens, microwave-puffing is expected to become one of the popular cooking methods for snack products. Therefore, many inventions related to the half products for at-home microwave puffing have been disclosed (Van Hulle et al 1983, Whalen and River 1992, Wilbur 1992). But the expansion behavior of extruded starch pellets by microwave-heating has not been studied. The objectives of this study were to investigate the effect of gelatinization and moisture content of the extruded starch pellets on microwave-puffing and physical properties of the expanded products, and to optimize the gelatinization and moisture levels for microwave-puffing.

## MATERIALS AND METHODS

Corn starch (13% moisture content) was provided by Samyang Genex, Ltd. (Seoul, Korea). Extrusion was performed in a pilot-scale corotating twin-screw extruder (Kobelco Extruder TCO-30, Kobe Steel, Tokyo, Japan) with three barrels. Screw diameter was 31 mm, and the ratio of barrel length to screw diameter was 25:1. A single-hole die with a diameter of 6 mm and a length of 20 mm was used. The extruder system and overall screw configuration are



- 1 : 1/2 pitch, 30 mm  
2 : 1/2 pitch, 30 mm, cutting flight  
3 : 1/2 pitch, 60 mm  
4 : 2/3 pitch, 60 mm  
5 : 3/4 pitch, 90 mm  
6 : full pitch, 90 mm

Fig. 1. Twin-screw extruder configuration used to prepare pellets.

<sup>1</sup> Foods R&D Center, Cheiljedang Corporation, Seoul 152-050, Korea.

<sup>2</sup> Graduate School of Biotechnology, Korea University, Seoul 136-701, Korea.

<sup>3</sup> Corresponding author. E-mail: limst@mail.korea.ac.kr Phone: 82-2-3290-3435, Fax: 82-2-927-5201.

shown in Fig. 1. Water was injected with a peristaltic pump directly into the extruder through a port near the feeding hopper. Barrel temperature (70–110°C) and water injection rate (21–63 g/min) were changed to control the degree of gelatinization, while the feeding rate was held constant at 87 g/min. Extrusion conditions are listed in Table I. The extrudate was manufactured in the form of nonexpanded strands that were cut into small pellets (3 mm length) using a rotating knife. The pellets were dried to a moisture content of  $11 \pm 0.2\%$  in a convection oven (40°C) and then equilibrated in a sealed polypropylene bag for 24 hr before microwave heating. The moisture content of the pellet was determined by drying the pellets in an oven (105°C) until the weight did not change.

To investigate the effect of moisture content of the pellets on microwave-expansion behavior, the pellets were prepared by extruding corn starch with sufficient water under constant conditions (screw speed 200 rpm, starch feeding rate 87 g/min, barrel temperature 100°C, and water injection rate 42 g/min), were dried to the desired moisture content (7–28%) in a convection oven (40°C). The moisture content of pellets was determined by at least three replicates using Approved Method 44-15A (AACC 2000).

The pellets were expanded by using a microwave oven (700W, RE-552N, Samsung, Seoul, Korea). Between tests, the microwave oven was opened and the chamber was rapidly cooled to room temperature using a mechanical fan. The pellets (30 g) were placed in a microwave popcorn bag (volume 3,100 mL) layered with a susceptor (100 × 160 mm<sup>2</sup>) at the bottom, and the bag was heat-sealed and heated for 70 sec at high power. During microwaving, the bag was opened by water vapor pressure from the pellets. The heating time (70 sec) was based on preliminary experiments for good puffing efficiency and was constant for all samples.

Degree of gelatinization of extruded starch pellets was measured by the  $\alpha$ -amylase and iodine method (Tsuge et al 1990).

Puffing efficiency was calculated as a percent ratio of the number of expanded pellets to total pellets. A pellet was counted as expanded when there was no hard part left after the microwave heating. Specific expansion bulk volume was calculated as a ratio of increased bulk volume by microwave expansion divided by the initial pellet weight. The bulk volume was measured in a 500-mL graduated cylinder. The bulk density was determined by volumetric replacement with hulled millet (Halek and Chang 1992):

$$D_{\text{sample}} = D_{\text{millet}} \times M_{\text{sample}}/M_{\text{millet}} \quad (1)$$

where  $D_{\text{sample}}$  and  $D_{\text{millet}}$  were the bulk densities (g/mL) of the expanded products and hulled millet, respectively, and  $M_{\text{sample}}$  and  $M_{\text{millet}}$  were the weights (g) of the products and hulled millet at the same volume, respectively.

The cross-sectional structure of the expanded products was coated with gold-palladium and examined with a scanning electron microscope (S-2380N, Hitachi, Tokyo, Japan) at an accelerating voltage of 15 kV.

Experimental data were analyzed using an analysis of variance and correlation procedure with a computer statistical package (SAS Institute, Cary, NC).

## RESULTS AND DISCUSSION

### Degree of Gelatinization

The degree of gelatinization of the extruded pellets was 44.3–74.4% under the extrusion conditions used in this study (Table I). There was a positive correlation between the degree of gelatinization and the barrel temperature for the extrusion ( $P < 0.05$ ). Water injection rate, however, had little effect on the degree of gelatinization. The water injection rate for the extrusion was relatively high (30–53% moisture content) and sufficient water was provided in this range, so the extrusion was processed with low shear. Therefore, starch gelatinization was not significantly dependent on the water injection rate.

### Morphology

As shown in Fig. 2, overall appearance of the extruded pellets was divided into three groups depending on the degree of gelatinization: opaque, translucent, and transparent. The opaque pellets were produced at the lowest barrel temperature (70°C) where degree of gelatinization was <50%. Translucent pellets were obtained when the degree of gelatinization was higher (52.7%) by extruding at 90°C with a water injection rate of 63 g/min. The pellets became transparent when the barrel temperature was 110°C and thus the degree of gelatinization was >65%. At 110°C, the cross-sectional area of the pellets was relatively larger than that of the pellets processed at lower temperatures. This result indicates that the pellets processed at 110°C had significantly higher degree of die swelling compared with those processed at lower temperatures.

The shape of microwave-expanded products was highly dependent on the appearance of the pellets (Figs. 2 and 3). When the pellets with a low degree of gelatinization (<50%) were microwaved, there was only a minor increase in volume (Fig. 2). Scanning electron micrography shows air voids inside the product at low gelatinization appeared relatively small, resulting in most of the solids between voids remaining intact. Ungelatinized starch granules were also seen (Fig. 3A).

The gas-retaining capability of starch was critical to the formation of stable and fine air cells in the expanded products, and this could be generated from sufficient viscoelasticity. The low degree of gelatinization was thus related to the low viscoelasticity that may result in insufficient expansion. In the pellets with less gelatinization, vapor evaporated from inside the pellet by heating might be discharged between swollen starch granules that were more or less fused. Therefore, small voids could be formed instead of air cells (Reeve and Walker 1969). On the other hand, the pellets with gelatinization >66% expanded into round shapes with large air cells with

TABLE I  
Extrusion Conditions, Degree of Gelatinization of Pellets, and Physical Properties of Microwave-Treated Products<sup>a</sup>

Treatment	Barrel Temperature <sup>b</sup> (°C)	Water Injection Rate <sup>c</sup> (g/min)	Degree of Gelatinization (%)	Puffing Efficiency (%)	Expansion Bulk Volume (mL/g)	Bulk Density (g/mL)
A	70	32	47.0e <sup>d</sup>	...	1.18d	0.62a
B	70	42	44.3e	...	0.72d	0.66a
C	70	63	46.7e	...	0.88d	0.60a
D	90	21	74.7a	82.7b	4.58b	0.28b
E	90	42	67.0c	79.3bc	4.69b	0.20b
F	90	63	52.7d	91.3a	10.68a	0.12c
G	110	21	73.6ab	71.7c	3.39c	0.27b
H	110	32	67.6c	72.9c	3.40c	0.33b
I	110	42	69.6bc	78.1bc	3.47c	0.33b
J	110	63	66.7c	83.6ab	3.04c	0.27b

<sup>a</sup> Measurements repeated three times for each treatment.

<sup>b</sup> Temperature of barrels 1 and 2 was constant at 70°C; barrel 3 was not heated.

<sup>c</sup> Barrel moisture contents were 30, 36, 41, and 53% for water injection rates of 21, 32, 42, and 63 g/min, respectively.

<sup>d</sup> Values followed by the same letter are not significantly different ( $P < 0.05$ ).

thick cell walls (Figs. 2 and 3B). This was probably caused by efficient formation and maintenance of air cells due to sufficient starch gelatinization of the pellets. Because of the viscoelasticity and film-forming ability of gelatinized starch, air cells may be formed easily and then expanded by successive buildup of vapor pressure without disrupting cell structure. As the result, large air cells with thick cell walls without ruptures in the outer layer of the pellet were responsible for the overall round shape of the expanded pellets.

However, pellets with 52.7% gelatinization (barrel temperature 90°C, water injection rate 63 g/min) showed unique expanded shape, different from the pellets with <50% or >65% gelatinization (Figs. 2 and 3C). These pellets underwent rapid rupture, and the center of each pellet was exposed to the outside (Fig. 2). Cross-sections of the expanded products showed almost uniformly distributed small air cells (Fig. 3C) that were very similar to those of commercial popcorn, although the latter had much smaller air cells (Fig. 3D). The unique shape was caused by the sudden release of the water vapor pressure that excessively built up inside the pellet. This might be similar to the rupture of the pericarp in popcorn (Hoseney et al 1983). Therefore, pressure buildup followed by sudden release was required for the microstructure formation with small air cells. But when pellets had insufficient gelatinization (<50%), buildup of vapor pressure inside the pellet might not be enough due to vapor discharge.

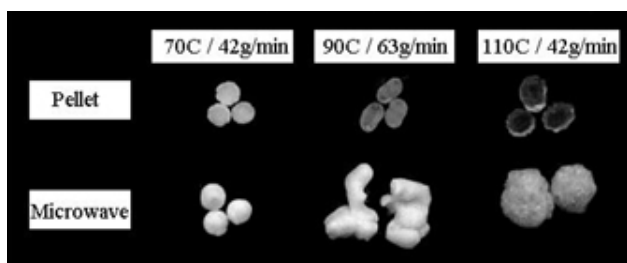


Fig. 2. Extruded pellets and microwave-heated products.

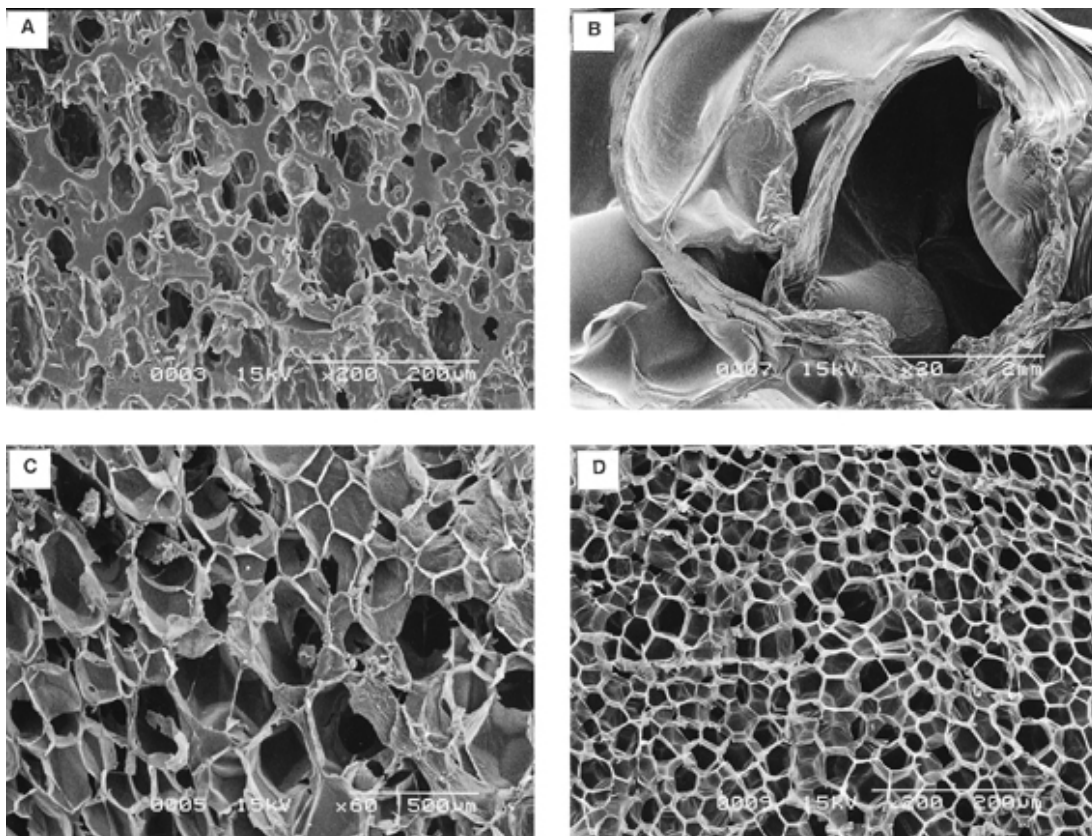


Fig. 3. Scanning electron micrographs of cross-sections of microwave-puffed products at different temperatures and water feeding rates: A, 70°C and 42 g/min (×200); B, 110°C and 42 g/min (×20); C, 90°C and 63 g/min (×200); D, commercial popcorn (×200).

For pellets with excess gelatinization (>65%), the pellets might be expanded over an extended time, resulting in continuous cell growth and thick cell wall.

### Puffing Efficiency

Several researchers pointed out that commercial microwave popcorn usually has a higher ratio of unpopped kernels than the conventional pan-heated popcorns (Lin and Anantheswaran 1988; Pordesimo et al 1990, 1991; Song et al 1991; Mohamed et al 1993; Song and Eckhoff 1994).

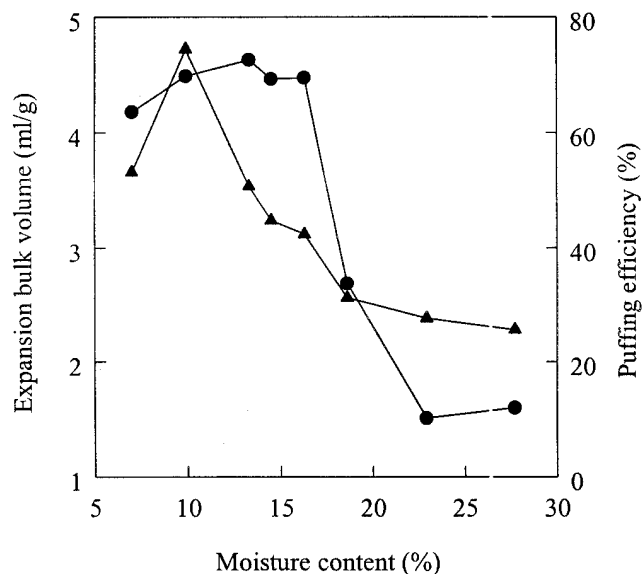


Fig. 4. Effect of moisture content of extruded pellets on expansion bulk volume (▲) and puffing efficiency (●).

The extruded pellets (11% moisture) prepared in this experiment were not fully expanded by microwave heating for 70 sec. The pellets produced at 70°C barrel temperature (<50% gelatinization) were rarely expanded. But the pellets processed at 90 or 110°C barrel temperature displayed puffing efficiency >70% (Table I). The pellets produced at 90°C with a water injection rate of 63 g/min (52.7% gelatinization) had a maximum puffing efficiency (91%), which indicates that 9 of 10 pellets were expanded. Thus, half-gelatinized pellets had optimum expansion behavior in microwave heating. This was because of the rupture by the sudden release of excessive internal pressure.

### Bulk Volume and Density

Expansion bulk volume of the microwave-expanded products from the pellets extruded at 70°C (<50% gelatinization) was low (0.88–1.18) (Table I). But the pellets extruded at 90 or 110°C showed significantly higher specific bulk volumes and lower bulk densities. For example, the pellets extruded at 90°C with a water injection rate of 63 g/min gave the best puffing efficiency (91.3%), the highest specific bulk volume (10.68 mL/g), and the lowest bulk density (0.12 g/mL) among the tested samples. The specific bulk volume of the microwaved products was positively correlated with puffing efficiency ( $P < 0.05$ ,  $r = 0.7196$ ).

The measurement of specific bulk volume of the expanded products using a graduated cylinder could not differentiate the expansion degree among the products because the product shapes were not uniform. Therefore, bulk density measured using millet provided more accurate comparisons for the degree of expansion.

Several researchers demonstrated that expansion ratio of the cereals by direct heating or extrusion depended on the degree of starch gelatinization (Chinnaswamy and Bhattacharya 1983, 1986; Bhattacharya and Hanna 1987; Chinnaswamy and Hanna 1988). Case et al (1992) reported that the volume of deep-fat-fried products with the extruded pellets increased as the degree of gelatinization increased. However, expansion bulk volume of the microwave-treated products did not show any linear relationship with the degree of gelatinization of pellets ( $P < 0.05$ ). The correlation between the bulk density of microwave-treated products and the degree of gelatinization of pellets was low ( $P < 0.05$ ,  $r = -0.701$ ). The data showed that the expansion by microwave was optimized at ≈50% gelatinization. This could be attributed to the unique expansion behavior of the extruded starch pellets subjected to microwave heating that are different from extrusion or frying expansion.

The specific bulk volume and puffing efficiency of the microwave-expanded products was measured at different moisture contents. For this test, the pellets were prepared with a barrel temperature of 100°C and a water injection rate of 42 g/min and then dried at 40°C to a desired moisture content.

### Moisture Effect

As shown in Fig. 4, maximum expansion bulk volume (4.72 mL/g) was achieved at 10% moisture content, whereas the puffing efficiency (72.6%) was highest at 13% moisture. Most of the pellets were not expanded when the moisture content was >20%. And the specific bulk volume declined rapidly as the moisture content in the pellet increased to >10%.

Similar results have been reported with natural popcorn (Lin and Anantheswaran 1988, Metzger et al 1989, Pordesimo et al 1991). Hosney et al (1983) explained that too much moisture content may contribute to weakening of the pericarp, resulting in a higher unpopped kernel ratio. For the uniform distribution of small-sized air cells with good puffing efficiency, the pellets should have a vapor pressure buildup followed by sudden release (puffing) during the microwave-heating. Therefore, too high a moisture content of pellets hinders the sudden vapor pressure release due to the lack of a pressure barrier. At low moisture content, there was insufficient superheated water for complete expansion, causing low expansion bulk volume and puffing efficiency.

Our results with microwave expansion also showed that the moisture content of pellets significantly affected the behavior and degree of expansion. The optimum moisture content for maximum expansion bulk volume and puffing efficiency was 10–13%.

The maximum puffing efficiency and bulk volume of the microwave-expanded products with extruded starch pellets achieved in this study were 91% and 12.4 mL/g, respectively. These values might not be high enough for commercial significance. But further improvements in the expansion characteristics could be achieved by optimizing the pellet composition and extrusion process. The extruded starch pellets have potential as a replacement of conventional popcorn. In addition, the starch pellets might be provided at a cheaper cost than natural popcorn and have more versatility in the composition, texture, and flavors.

## CONCLUSIONS

Extruded starch pellets can be puffed by a conventional microwave oven at home like commercial microwave popcorn. Degree of gelatinization and moisture content of the pellets were two of the most important factors in determining the shape, expansion bulk volume and density, and puffing efficiency of the microwaved products. For uniform distribution of small-sized air cells with good puffing efficiency, the pellets should have a sudden release of vapor pressure buildup inside pellets during microwave heating. Optimal expansion by microwave heating was achieved when the starch was approximately half-gelatinized and the moisture content in the pellets was ≈10%.

## LITERATURE CITED

- American Association of Cereal Chemists. 2000. Approved Methods of the AACC, 10th ed. Method 44-15A. The Association: St. Paul, MN.
- Anonymous. 1998. Process description—Snack food production. SFP-200-GRH. Wenger Manufacturing: Sabetha, KS.
- Bhattacharya, M., and Hanna, M. A. 1987. Textural properties of extrusion-cooked corn starch. *Lebensm. Wiss. Technol.* 20:195-201.
- Case, S. E., Hamann, D. D., and Schwartz, H. G. 1992. Effect of starch gelatinization on physical properties of extruded wheat- and corn-based products. *Cereal Chem.* 69:401-404.
- Chinnaswamy, R., and Bhattacharya, K. R. 1983. Studies on expanded rice: Optimum processing conditions. *J. Food Sci.* 48:1604-1608.
- Chinnaswamy, R., and Bhattacharya, K. R. 1986. Pressure-parboiled rice: A new base for making expanded rice. *J. Food Sci. Technol.* 23:14-19.
- Chinnaswamy, R., and Hanna, M. A. 1988. Optimum extrusion-cooking conditions for maximum expansion of corn starch. *J. Food Sci.* 53:834-840.
- Halek, G. W., and Chang, K. L. B. 1992. Effect of extrusion operation variables on functionality of extrudates. Pages 677-691 in: *Food Extrusion Science and Technology*. J. L. Kokini, C. T. Ho, and M. V. Karwe, eds. Marcel Dekker: New York.
- Harper, J. M. 1989. Food extruders and their application. Pages 1-15 in: *Extrusion Cooking*. C. Mercier, P. Linko, and J. M. Harper, eds. Am. Assoc. Cereal Chem.: St. Paul, MN.
- Hosney, R. C., Zeleznak, K., and Abdelrahman, A. 1983. Mechanism of popcorn popping. *J. Cereal Sci.* 1:43-52.
- Kim, S. L., Park, S. U., Cha, S. W., and Seo, J. H. 1995. Major characteristics affecting popping volume of popcorn. *Korean J. Crop Sci.* 40:167-174.
- Lin, Y. E., and Anantheswaran, R. C. 1988. Studies on popping of popcorn in a microwave oven. *J. Food Sci.* 53:1746-1749.
- Metzger, D. D., Hsu, K. H., Ziegler, K. E., and Bern, C. J. 1989. Effect of moisture content on popcorn popping volume for oil and hot-air popping. *Cereal Chem.* 66:247-248.
- Mohamed, A. A., Ashman, R. B., and Kirleis, A. W. 1993. Pericarp thickness and other kernel physical characteristics relate to microwave popping quality of popcorn. *J. Food Sci.* 58:342-346.
- Pordesimo, L. O., Anantheswaran, R. C., Fleischmann, A. M., Lin, Y. E., and Hanna, M. A. 1990. Physical properties as indicators of popping characteristics of microwave popcorn. *J. Food Sci.* 55:1352-1355.
- Pordesimo, L. O., Anantheswaran, R. C., and Mattern, P. J. 1991. Quantification of horny and floury endosperm in popcorn and their effects on popping performance in a microwave oven. *J. Cereal Sci.*

14:189-198.

- Reeve, R. M., and Walker, H. G. 1969. The microscopic structure of popped cereals. *Cereal Chem.* 46:227-241.
- Song, A., and Eckhoff, S. R. 1994. Optimum popping moisture content for popcorn kernels of different sizes. *Cereal Chem.* 71:458-460.
- Song, A., Eckhoff, S. R., Paulsen, M., and Litchfield, J. B. 1991. Effects of kernel size and genotype on popcorn popping volume and number of unpopped kernels. *Cereal Chem.* 68:464-467.
- Tsuge, H., Hishida, M., Iwasaki, H., Watanabe, S., and Goshima, G. 1990. Enzymatic evaluation for the degree of starch retrogradation in foods and foodstuffs. *Starch/Staerke* 42:213-216.
- Van Hulle, G. J., Anker, C. A., and Franssell, D. E. 1983. Method for preparing sugar coated, puffed snacks upon microwave heating. U. S. patent 4,409,250.
- Whalen, P., and River, E. 1992. Half products for microwave puffing of expanded food product. U. S. patent 5,102,679.
- Wilbur, D. H. 1992. Puffable cereal pellets which pop upon microwave heating and method of preparation. U. S. patent 5,108,772
- Wu, P., and Schwartzberg, H. G. 1992. Popping behavior and zein coating of popcorn. *Cereal Chem.* 69:567-573.

[Received February 7, 2000. Accepted June 23, 2000.]