A Thesis for the Degree of Master of Science

Physicochemical and digestion properties of starches from sweet potato mutants obtained with gamma irradiation

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농학석사학위논문

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Physicochemical and digestion properties of starches from sweet potato mutants obtained with gamma irradiation

by

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ABSTRACT

The physicochemical, digestion, and pasting characteristics of starches isolated from Korean sweet potato cultivar (Shingeonmi) mutants were investigated. The sweet potato stems were irradiated with 0.1 kGy dose of a ^{60}Co source with a rate of 5 Gy/h (0 Gy as a control), and seven plant lines (MS1-7) were examined. The yields of 100 g or more storage roots of control and MS1-7 were 44.71, 52.94, 46.44, 38.80, 52.81, 32.12, 25.90 and 50.41%, respectively. The mean volume diameter ($d_{4,3}$) of the mutant starch granules had a wide range of between 12.98 and 43.91 μm, while there was no change in the granule shapes. Amylose contents and branch chain length distributions of the starches were not significant different. All the starches exhibited a C_a-type of X-ray diffraction pattern. The relative crystallinities varied from 44.70 to 51.03%, and MS5 and MS1 had the lowest and highest crystallinity, respectively. The higher T_o and T_p of MS1 implied that the starch had a higher degree of structural stability as well as the higher crystallinity. MS1 showed the lower swelling and pasting behaviors, which are most likely due to the higher relative crystallinity and the smaller granule size. The storage modulus (G') and loss modulus (G") of all the starches increased with an increase in angular frequency, but the G' was greatly

higher than the G", a characteristic of gel, showing solid-like behavior. MS1 showed the lower viscoelastic behavior than the other starches. Both the raw and cooked starches of MS1 showed the lower digestibility, but the digestibilities of other mutant starches were not significantly different compared to the control. In conclusion, these results suggested that gamma irradiation had an influence on the morphological, pasting, rheological, and digestion properties of starches and the potential applicability of the mutant starches in food industry.

Keywords: sweet potato starch, gamma irradiation, mutant starch, physicochemical properties, *in vitro* digestibility

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INTRODUCTION

Starch is the major storage form of carbohydrates in plants and an important source in human diet. It consists of two α-glucans, amylose and amylopectin. Amylose is an essentially linear molecule of α-1,4 linked anhydroglucose residues with a few branches, and amylopectin is a branched molecule comprising chains of α-1,4 linked anhydroglucose residues linked by α-1,6 branch points (Gidley et al., 2010). Starch are used as a thickener, stabilizer, gelling agent, bulking agent, water retention agent and adhesive in food industry. The morphological, rheological, thermal and textural characteristics of starch contribute to the functionality of many foods (Singh et al., 2003). For nutritional purpose, starch is classified into rapidly digestible starch (RDS), slowly digestible starch (SDS), and resistant starch (RS) depending on the rate and extent of starch digestibility (Englyst et al., 1992).

Sweet potato (*Ipomoea batatas* (L.) Lam.) is one of the important root crops and staple food in the world, especially in Asia. Sweet potato starch has been widely used as an ingredient for products such as noodles, soup, sauce, snacks, and breads (Kim et al., 2013). Singeonmi is a Korean sweet potato cultivar which was selected from the cross between Mokpo22 and

Shinyulmi. Singeonmi is resistant to fusarium wilt caused by *Fusarium oxysporum* f. sp. Batatas, has a starch content of 25.4%, and thus it has been utilized for food and starch production (Ahn et al., 2002).

Over the past years, conventional breeding techniques have significantly contributed toward improvements in sweet potato including its yield, nutritional value, and disease resistance (Zhou et al., 2015). However, improvement of sweet potato variety by traditional methods based on sexual hybridization has some inconvenient problems such as sterility and cross-incompatibility, and thus their poor diversity in starch traits limits the range of use (Kitahara et al., 2007; Otani et al., 1998). Therefore, modifications are necessary to expand the range of applications.

Breeding changes the genetics of plants in order to produce desired characteristics such as quality and yield, tolerance to environmental pressures, resistance to viruses, fungi, and bacteria, and tolerance to herbicides. In breeding, there are three different kinds of ways, isolation breeding, cross breeding, and mutation breeding. Among these, mutation breeding is a process of exposing seeds to chemicals or radiation, induces mutations, and generates genetic variations. Mutation breeding could be a promising approach for improving sweet potato varieties, since it is a clonally propagated crop (Shin et al., 2011).

Among the mutation breeding methods, gamma irradiation is a fast, low cost and environment-friendly alternative method, improving characteristics disease resistance, starch content, soluble sugar content, carotenoids content, etc. in sweet potato (Kukimura et al., 1986; Wang et al., 2007). The impact of gamma irradiation depends on the dosage and condition. The radiation doses can be divided into three broad categories: high (> 10 kGy), medium (1-10 kGy), and low (<1 kGy). The high doses are usually used for the sterilization of products in food industry, and the low doses are used to induce mutations in seeds, where doses range from 60 to 700 Gy for many seed propagated crops (Ahloowalia & Maluszynski, 2001).

Several studies about the effects of gamma irradiation on starches from different botanical sources have been reported. When starch is directly irradiated with gamma rays, free radicals are generated on starch molecules that could induce degradation and/or cross-linking of the starch chains (Bhat & Karim, 2009; Kang et al., 1999). These molecular changes could affect the structure, physicochemical properties, and digestibility of starch (Lee et al., 2013). Yoon et al. (2010) and Lee et al. (2013) observed a significant increase of RS in both normal and waxy corn starches irradiated with 5, 10, and 20 kGy. Gani et al. (2012) postulated that gamma irradiation induces an increase in solubility, water absorption capacity and a decrease in swelling

index and amylose content in bean starches. They are reported that the pasting properties decrease significantly with increasing irradiation dose. The starch having a small granule size and high-amylose content is identified from the mutants when cassava seeds are irradiated with gamma rays (Ceballos et al., 2008). Recently, Shin et al. (2011) applied gamma irradiation mediated mutation breeding to a Korean sweet potato cultivar in order to produce useful varieties having a high yield and a high starch content. However, there is little information on the starch properties of gamma irradiated mutant crops.

Thus, the objectives of this study were to characterize the physicochemical properties and digestibility of sweet potato mutant starches induced by gamma irradiation and to evaluate the potential applicability of the mutant starches in food industry.

MATERIALS AND METHODS

1. Materials

Sweet potato (Singeonmi) mutant lines were obtained from University of Seoul (Seoul, Korea). Sweet potato stems with axillary buds cut from the sweet potato grown in a greenhouse, under natural day length were used as experimental material after removing leaves and exposure to 0.1 kGy dose of a ^{60}Co source with a rate of 5 Gy/h. The irradiation treatments were performed at the Advance Radiation Technology Institute (Jeongeup, Korea). The gamma-irradiated stems with axillary buds were excised from two or three nodes, and immediately planted in garden soil. A non-irradiated sweet potato (as a control) and seven mutant lines (MS1-7) were used for this study. The yield of 100 g or more storage roots of control and MS1-7 were 44.71, 52.94, 46.44, 38.80, 52.81, 32.12, 25.90 and 50.41%, respectively.

Isoamylase (activity 1000U/mL) was obtained from Megazyme (Bray, Ireland), pancreatin (P7545, activity 8 × USP/g) was from Sigma Chemical Co. (St. Louis, MO, USA) and amyloglucosidase (AMG 300L, activity 300 AGU/mL) from Novozymes (Bagsvaerd, Denmark).

2. Methods

2-1. Starch isolation

The sweet potato tubers were thoroughly washed with tap water and peeled. The peeled samples were sliced into 0.2mm thick pieces using a food slicer and blended for 2 min with distilled water at a low speed setting, using a blender (HR2094, Koninklijke Philips N.V., Amsterdam, Netherlands). The blended slurry was passed through 35-, 50-, and 100-mesh sieves, and then the residue was mixed with distilled water (1:3 v/v) and blended twice more and the suspension was collected in a plastic container. After a solid layer of starch settled down, the supernatant was decanted, and the starch layer was dissolved in 0.1% NaOH solution. The starch precipitate was washed with distilled water and this process was repeated until the supernatant became transparent. Finally, the suspended solution was centrifuged at 1,500 ×g for 10 min. Then, the starch was dried at 50°C in a drying oven for 24 h, ground and passed through a 100-mesh sieve.

2-2. Granular shape and size

The particle size of sweet potato starch was measured using a laser particle size analyzer (BT-9300ST, Bettersize Instruments Ltd., China), including the mean volume diameter, $d_{4,3.}$

The granule morphology of sweet potato starches were observed using a scanning electron microscopy (SEM). Starch samples were mounted on circular aluminium stubs with double sticky carbon tape, coated with a thin film of platinum under vacuum, and examined with a field-emission scanning electron microscope (Supra 55VP, Carl Zeiss, Oberkochen, Germany) at an accelerating potential of 1 kV.

2-3. Amylose content

Absolute amylose contents of the sweet potato starches were determined with an amylose/amylopectin assay kit (Megazyme International Ireland Ltd.) based on the concanavalin A method of Gibson et al. (1997).

2-4. Branch chain length distribution

The branch chain length distribution of amylopectin of starch sample was determined after debranching the starch with isoamylase. Starch (15 mg) was dispersed in 90% DMSO (3 mL) and boiled for 20 min. To precipitate the

starch, ethanol (15 mL) was added to starch suspension. The suspension was centrifuged at 10,000 ×g for 10 min twice. Distilled water (1.5 mL) was added to the precipitated starch pellet and boiled for 10 min. After boiling, 50 mM sodium acetate buffer (pH 4.3, 1.5 mL) was added and boiled for 15 min. After cooling to 45°C for 30 min, isoamylase (30 μL) was added to the starch dispersion and the sample was incubated at 45°C and 30 rpm for 2 h in a water bath. The enzyme reaction was stopped by boiling for 10 min. Debranched sample was filtered through a 0.45 μm membrane filter and analyzed using HPAEC-PAD on an Carbo-pak PA1 anion-exchange column (4×250 mm, Dionex, Sunnyvale, CA, USA) with a pulsed amperometric detector. The sample was eluted with a gradient of 600 mM sodium acetate in 150 mM NaOH with a flow rate 1 mL/min. The gradients of sodium acetate used were as follows: 0-20 % for 0-5 min, 20-45 % for 5-30 min, 45-55 % for 30-60 min, 55-60% for 60-80 min, 60-65 % for 80-90 min, 65-80 % for 90-95 min, and 80-100 % for 95-100 min. The values of DP were designated using a mixture of maltooligosaccharides (DP 1-7, Sigma Chemical) as standard. PeakNet software (version 5.11, Dionex) was used for calculation of peak areas. Number-based average DP (DP_n) was determined by the following equation

$$DP_n = (\%A_i \times DP_i) / 100$$

A_i : peak area / total area (i: 1, 2, 3 …)

2-5. X-ray diffraction patterns and relative crystallinity

X-ray diffraction was analyzed using a powder X-ray diffractometer (New D8 Advance, Bruker, Karlsruhe, Germany) at 40 kV and 40 mA. Starch sample scan was performed through 2θ range from 3° to 30° with a 0.02° step size and a count time of 2 sec. The relative crystallinity was determined by the following equation according to the method of Nara & Komiya (1983). The area was calculated using the software developed by the instrument manufacturer (EVA, 2.0).

$$\text{Relative crystallinity (\%)} = \left(\frac{\text{Crystalline area}}{\text{Total curve area}}\right) \times 100$$

2-6. Thermal properties

Thermal properties of the sweet potato starches were measured using a differential scanning calorimeter (DSC, Diamond DSC, Perkin-Elmer, Waltham, MA, USA). Starch (10 mg) was weighed in a hermetic aluminum pan (Seiko, Tokyo, Japan), and 40 μL of distilled water was added. The sample pan was sealed and kept at room temperature overnight for equilibrium. An empty aluminum pan was used as a reference. DSC scan was

made as the sample was heated from 30°C to 130°C at a scan rate of 5°C/min.

2-7. Swelling factor

Swelling factor of starch was determined according to the method of Tester & Morrison (1990). Starch (100 mg) was suspended in 5 mL of distilled water and incubated in a shaking water bath (30 rpm) at 50, 60, 70 and 80°C for 30 min. After cooling the sample on ice, blue dextran solution (0.5 mL, 5mg/mL) was added. The solution was centrifuged at 3,000 ×g for 15 min, and the absorbance of the supernatant was measured at 620 nm. Swelling factor (SF) was calculated as follows:

$$SF = 1 + \frac{7{,}700}{w} \times \frac{A_S - A_R}{A_S}$$

w : sample weight (mg)

A_S : absorbance of the supernatant

A_R : absorbance of reference (without starch)

2-8. Pasting properties

Pasting properties of starch suspensions were measured with a Rapid Visco Analyser (RVA-4, Newport Scientific Pty, Ltd., Warriewood, Australia). Each sweet potato starch (2 g) was added to 25 mL of distilled water. The starch suspension was equilibrated at 50°C for 1 min, heated from 50 to 95°C at a rate of 12°C/min, held at 95°C for 2.5 min, cooled to 50°C at the same rate, and held at 50°C for 2 min. The paddle speed was 960 rpm for the first 10 sec, then 160 rpm for the remainder of the experiment.

2-9. Rheological properties

The rheological properties of sweet potato starches were assessed using an oscillatory rheometer (Rheostress 1, Thermo HAKKE, Karlsruhe, Germany) with a plate-plate system (60 mm diameter, 1 mm gap). Starch suspension (5 %, w/v) was placed between the plate and plate in a rheometer. The suspension was heated from 25°C to 95°C at a rate of 5°C/min, held at 95°C for 10 min, cooled to 25°C at the same rate, and then held at 25°C for 1 h to form starch gel. A thin layer of silicon oil was added to prevent water evaporation. The frequency sweep measurement was carried out in a frequency range of 0.1-10 Hz at 25°C. All measurement was performed in

the linear viscoelastic region. Storage modulus (*G'*) and loss modulus (*G''*) were obtained.

2-10. Starch digestibility

The digestibility of uncooked and cooked starches were determined following the method of Englyst et al. (1992) with slight modification. To prepare enzyme solution, pancreatin (1.5 g) was dissolved in distilled water (18 mL) and stirred for 10 min. It was precipitated by centrifugation at 1,500 ×g for 10 min, and the supernatant was transferred into a beaker containing 2.7 mL of distilled water and 0.3 mL of amyloglucosidase. The enzyme solution was incubated at 37°C for 10 min.

A starch sample (30 mg) was dispersed in a 2 mL-microtube with sodium acetate buffer (0.1 M, pH 5.2, 0.75 mL) with a glass bead. It was then equilibrated in a shaking incubator (240 rpm, 37°C) for 10 min, the prepared enzyme solution (0.75 mL) was added to the tube, and the starch sample was incubated in a shaking incubator (240 rpm, 37°C). The enzyme reaction was stopped at 10 min and 240 min by boiling for at least 10 min. The hydrolyzed glucose in the supernatant was obtained by centrifugation at 5,000 ×g for 10 min. The glucose content was determined by the glucose oxidase method (Karkalas, 1985) using a commercially available kit (Embiel

Co., Gunpo, Korea). To measure the content of released glucose, 11-fold diluted supernatant (0.1 mL) was added to a 2mL-microtube containing 1.5 mL of glucose oxidase and peroxidase (GOD-POD) reagent. The microtube was incubated in a water bath at 37°C for 20 min. The absorbance of the sample was then read at 505 nm.

Cooked sample was prepared by boiling starch dispersions with the sodium acetate buffer (0.1 M, pH 5.2, 0.75 mL) for 10 min before equilibrating to 37°C in a shaking incubator (240 rpm, 37°C).

Starch fractions were classified based on the rate and degree of hydrolysis. RDS was measured by the value of glucose after enzyme reaction for 10 min, SDS was defined as the amount digested between 10 min and 240 min of hydrolysis, and the undigested fraction after 240 min was determined as RS.

2-11. Statistical analysis

All the experiments were performed in triplicate, and data were expressed as mean ± standard deviation. Analysis of variance (ANOVA) was conducted and the significant differences among mean values were compared using the Duncan's multiple range test ($p<0.05$). Statistical analysis was conducted by IBM SPSS statistics version 21.0 (IBM, NY, USA).

RESULTS AND DISCUSSION

1. Morphological characteristics of starch granules

The morphological characteristics of starch granules isolated from sweet potato mutants induced by gamma irradiation were studied using particle size analysis and scanning electron microscopy. Starch granule size is an important parameter that affects its physicochemical properties and applications. It was reported that gamma irradiation generates free radicals on starch molecules which changes molecular size and structures when starch is directly irradiated by gamma rays (Ciesla et al., 1991). Gamma irradiation is capable of hydrolyzing chemical bonds, thereby cleaving large molecules of starch into smaller fragments of dextrin that may be either electrically charged or uncharged as free radicals (Kang et al., 1999). These deformations were observed in corn starches (Lee et al., 2006).

The particle size characteristics of sweet potato starches are presented in Table 1. The sweet potato mutant starches had a wide range of granule size distributions, 12.98-43.91 μm, and the control starch showed a granule size of 26.88 μm. The smallest and largest size in mutant starches was MS1 and MS7, respectively. The differences in granule size among the starches are

most likely due to the termination of starch synthesis at different development stages (Geddes et al., 1965, Pan et al., 2000).

The scanning electron micrographs of control and mutant starches are shown in Fig. 1. Sweet potato starches had round, oval, bell, and irregular shaped granules, and there were no significant differences between control and mutant starches with respect to the granule shape. MS1 showed higher proportions of small starch granules than the control and other mutant starches, consistent with the result of particle size analysis.

Many factors affecting starch granule morphology and size are not fully understood, and starch biosynthesis is a complicated and not clearly characterized process (Davis et al., 2003; Jobling, 2004). Despite the incomplete understanding of the relationships between starch granule structure, starch composition, and the functional properties of starch, several studies related to the starch biosynthesis have been reported.

Ceballos et al. (2008) reported that a lack of isoamylase activity is accompanied by an increase in the number of granules initiated resulting in a decrease in granule size. They also observed that the mutant cassava starch obtained with gamma irradiation had a small granule size (mutant genotype, 5.80 μm; wild type, 18.73 μm), a higher-than-normal amylose content, and low viscosity peaks. Burton et al. (2002) and Bustos et al. (2004) suggested

that small granules are characteristic of mutants lacking isoamylase activity. It has been reported that there are three types of isoamylase, *Isa1*, *Isa2*, and *Isa3*. Among these, *Isa1* and *Isa2* are considered to be responsible for normal starch synthesis (Bustos et al., 2004). In addition, small starch granule is seen in mutants lacking starch synthase (SS) or starch-branching enzyme (SBE) (Morell et al, 2003; Lloyd et al., 1996). Therefore, the small granule size of MS1 could be attributed to the decrease in the activities of isoamylase (*Isa1* and/or *Isa2)*, starch synthase (SS) or starch-branching enzyme (SBE) by gamma irradiation in the present study.

Table 1. Granule sizes of sweet potato starches

Sample[1)]	$d_{4,3}$[2)] (μm)
Control	26.88±0.53[c]
MS1	12.98±0.03[e]
MS2	17.42±3.03[d]
MS3	18.59±0.94[d]
MS4	21.27±0.85[d]
MS5	27.59±0.22[c]
MS6	32.37±2.73[b]
MS7	43.91±0.76[a]

[1)] Control = non-irradiated starch; MS1-7 = gamma-irradiated mutant starches.

[2)] $d_{4,3}$ = mean volume diameter.

[3)] The values with different superscripts in the same column are significantly different (p<0.05).

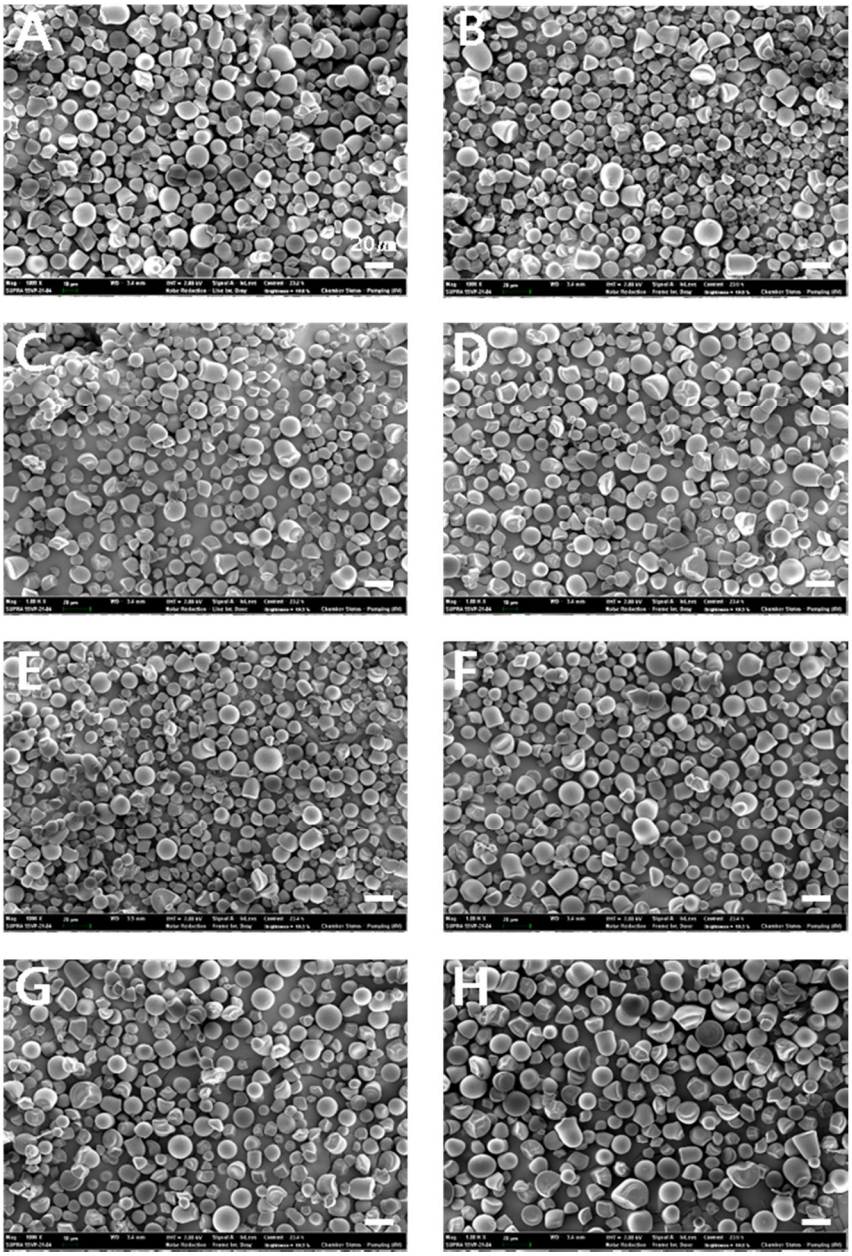

Figure 1. Scanning electron micrographs (×1000) of sweet potato starches at an accelerating potential of 1 kV: (A) control, (B) MS1, (C) MS2, (D) MS3, (E) MS4, (F) MS5, (G) MS6, (H) MS7.

2. Amylose content

Differences in amylose content among starches affect gelatinization and retrogradation properties, swelling power, and enzymatic susceptibility of starches (Gérard et al., 2001; Lindeboom et al., 2004). According to Shen & Sterling (1981), sweet potato starch has an amylose content of 13.4-22.5% depending on the variety, whereas values from 20 to 30% of amylose were reported by Waramboi et al. (2011).

The absolute amylose content of sweet potato starches ranged from 14.14 to 15.98% (Table 2). So far, several starch-related genes, especially amylose, have been identified in a range of plant species. Visser et al. (1991) suggested that an amylose-free starch is produced by suppressing granule-bound starch synthase I (GBSSI), which is known as waxy protein. On the other hand, high amylose starches are found by suppressing one isoform of starch-branching enzyme (SBEII) or by suppressing both SBEII and SBEI both (Blennow et al., 2005; Jobling et al., 1999; Schwall et al., 2000) . In the case of sweet potatoes, transgenic sweet potato having amylose-free starch was obtained by controlling GBSSI (Kimura et al., 2001), which was the first demonstration of the production of an amylose-free sweet potato mutant line. Shimada et al. (2006) reported that the increase in apparent amylose content in the sweet potato starch was found by inactivating SBEII. Thus, no

differences in the amylose contents of control and mutant starches used in this study indicated that the gamma irradiation did not affect the activities of the enzyme involved in amylose synthesis such as GBSSI and SBEII. In contrast, direct gamma irradiation of isolated potato and bean starches causes a significant reduction of amylose content compared with their native starches due to severe degradation of amylose fraction (Chung & Liu, 2010; Gani et al., 2012).

Table 2. Absolute amylose content of sweet potato starches

Sample[1)]	Absolute amylose content (%)
Control	14.18±0.69[a]
MS1	15.84±0.64[a]
MS2	15.33±2.26[a]
MS3	15.98±1.08[a]
MS4	14.84±1.14[a]
MS5	15.67±1.12[a]
MS6	14.57±0.76[a]
MS7	14.14±0.97[a]

[1)] Control = non-irradiated starch; MS1-7 = gamma-irradiated mutant starches.

[2)] The values with the same superscript in a column are not significantly different ($p>0.05$).

3. Branch chain length distributions

Branch chain length distribution of amylopectin is an important factor in determining functional properties of starch in food systems (Zhang & Hamaker, 2012). A higher proportion of short branch chains contributes to lower crystallinity, viscosity, and degree of retrogradation (Jane et al., 1999), whereas longer branch chains are responsible for the higher degree of retrogradation, gel firmness, and lower degree of digestibility (Zhang & Hamaker, 2012).

Branch chain length distributions of all samples totally debranched by isoamylase were analyzed using HPASEC-PAD. Amylopectin branch chains are classified into A chain (DP 6-12), B1 chain (DP 13-24), B2 chain (DP 25-36), and B3 chains (DP ≥ 37) depending on DP (Hanashiro et al., 1996).

Table 3 represents the relative percentages of total peak area with the degree of polymerization (DP) and the average DP of the control and mutant starches. In the current study, there were negligible differences in the proportions of chains and the average DP among the sweet potato starches; DP 6-12 (28.77-31.39%), DP 13-24 (50.32-51.71%), DP 15-36 (12.59-14.71%), DP ≥ 37 (3.96-5.66%), and average DP (17.55-18.56).

It has been suggested that GBSSI plays a role in not only the synthesis amylose but also the synthesis of amylopectin (van de Wal et al., 1998). The

transgenic sweet potato having amylose-free starch has a slightly lower content of short branch chains (DP 6-8) than that of the control (Noda et al., 2002). In the case of SBEII activity, there are considerable differences in the distributions of the branch chains between the SBEII-RNAi amylopectin and the non-transgenic amylopectin: a decrease in the chains with DP 6-11 and increases in the chains with DP 12-15 and DP 24-33 for the high-amylose starches by suppressing SBEII activity (Kitahara et al., 2007). However, there were no significant differences in the content of the A chains (DP 6-12) and even in the B1 (DP 13-24) and B2 (DP 25-36) chains between the control and the mutant starches (MS1-7), indicating that the expressions of GBSSI and SBEII were not affected by the gamma irradiation, and it was consistent with the results of amylose content in the present study.

Table 3. Branch chain length distributions of sweet potato starches

Sample[1)]	Percent distribution (%)				Average DP
	DP[2)] 6-12	DP 13-24	DP 25-36	DP ≥ 37	
Control	29.78±0.73^{abc}	50.66±0.86^{a}	14.09±0.67^{a}	5.47±0.42^{a}	18.35±0.16^{a}
MS1	31.68±0.24^{a}	51.51±0.28^{a}	12.59±0.04^{b}	4.23±0.08^{bc}	17.56±0.02^{b}
MS2	29.31±0.65^{abc}	50.32±0.95^{a}	14.71±0.04^{a}	5.66±0.27^{a}	18.56±0.04^{a}
MS3	28.95±0.94^{bc}	51.40±0.87^{a}	14.42±0.18^{a}	5.23±0.11^{ab}	18.42±0.05^{a}
MS4	28.77±0.63^{c}	51.28±0.60^{a}	14.61±0.16^{a}	5.34±0.13^{a}	18.49±0.03^{a}
MS5	29.62±1.61^{abc}	50.99±0.40^{a}	14.06±0.90^{a}	5.33±0.31^{a}	18.30±0.40^{a}
MS6	30.91±0.48^{abc}	51.71±0.36^{a}	12.74±0.22^{ab}	4.64±0.10^{abc}	17.79±0.04^{ab}
MS7	31.39±0.92^{ab}	51.55±0.27^{a}	13.11±0.03^{ab}	3.96±1.16^{c}	17.55±0.48^{b}

[1)] Control = non-irradiated starch; MS1-7 = gamma-irradiated mutant starches.

[2)] DP = degree of polymerization.

[3)] The values with different superscripts in the same column are significantly different (p<0.05).

4. X-ray diffraction patterns and relative crystallinity

The crystalline nature of a starch granule can be defined by the position of the X-ray diffraction peaks (Zobel, 1988), and starch granules from various botanical origins have one of three X-ray diffraction patterns, A-, B-, and C-type (Hizukuri et al., 1980). The traditional view is that most cereal starches, normal maize, rice, wheat, and oat generate A-type, alternatively called the cereal type; tubers, potato, lily, and high amylose starches show B-type; and some roots, legume, fruit and stem , sweet potato, taro, and iris starches show C-type pattern (Buléon et al., 1998; Hizukuri, 1996). Hizukuri et al. (1960) proposed that the C-type is a mixture of A- and B-type by various proportions, and the C-type diffraction pattern is characterized by a weak peak at 5.5° and distinct intensities at 15.2°, 17.1°, 18.2° and 23.1° 2θ angles. The C-type pattern can be further divided into C_a-, C_b-, and C_c-type on the basis of their resemblance to either A-type, B-type, or a type between A and B, respectively. A-type diffraction pattern displays main peaks at 15.0°, 17.0°, 17.9°, and 23° 2θ angles (Hanashiro et al., 1996).

The X-ray diffraction patterns and relative crystallinities of the sweet potato starches are given in Figure 2 and Table 4, respectively. It was reported that the starches of transgenic sweet potato modified by suppressing starch-branching enzyme II (SBEII) showed B-type diffraction pattern,

whereas the starches obtained by suppressing granule-bound starch synthase I (GBSSI) showed the same diffractograms of C-type as that of the normal starch. All the sweet potato starches used in this study belong to the Ca-type with peaks at 15°, 17°, 18° and 23° 2θ angles (Figure 2).

In spite of the similarity in X-ray diffraction pattern, significant differences were observed in the RC among the sweet potato starches (Table 4). The RC of the sweet potato starches ranged from 44.13 to 51.03%, which were within the range (25.5-56.0%) reported for other Korean sweet potato starches (Baek et al., 2014; Song et al., 2013). Compared with the control, the RC of MS1 increased by 6.33%p. Abdel-Aal et al. (2002) and Vandeputte et al. (2003) reported that RC differences amongst starches are related to amylopectin content, branch chain length distribution of amylopectin, crystallite size, molecular order and granule swelling. However, there were no significant differences in amylose contents (Table 2), indicating that RC of the sweet potato starches was not related to amylopectin content, branch chain length distributions (Table 3) and crystal size (indicated by differences in the sharpness of the X-ray spectrum, Figure 2) of control and the mutant starches. Therefore, the higher RC of MS1 was most likely due to stronger interaction between double helices within the crystalline lamella than control. In the case of maize and bean starches which are directly exposed to gamma

rays, the irradiated starches show no significant change in diffraction pattern as compared to non-irradiated starch. However, the relative crystallinities of the maize and bean starches decrease with increasing radiation dose due to destruction of long range ordering linked to the ordered structure of crystalline and amorphous regions in starch granules (Gani et al., 2012; Liu et al., 2012).

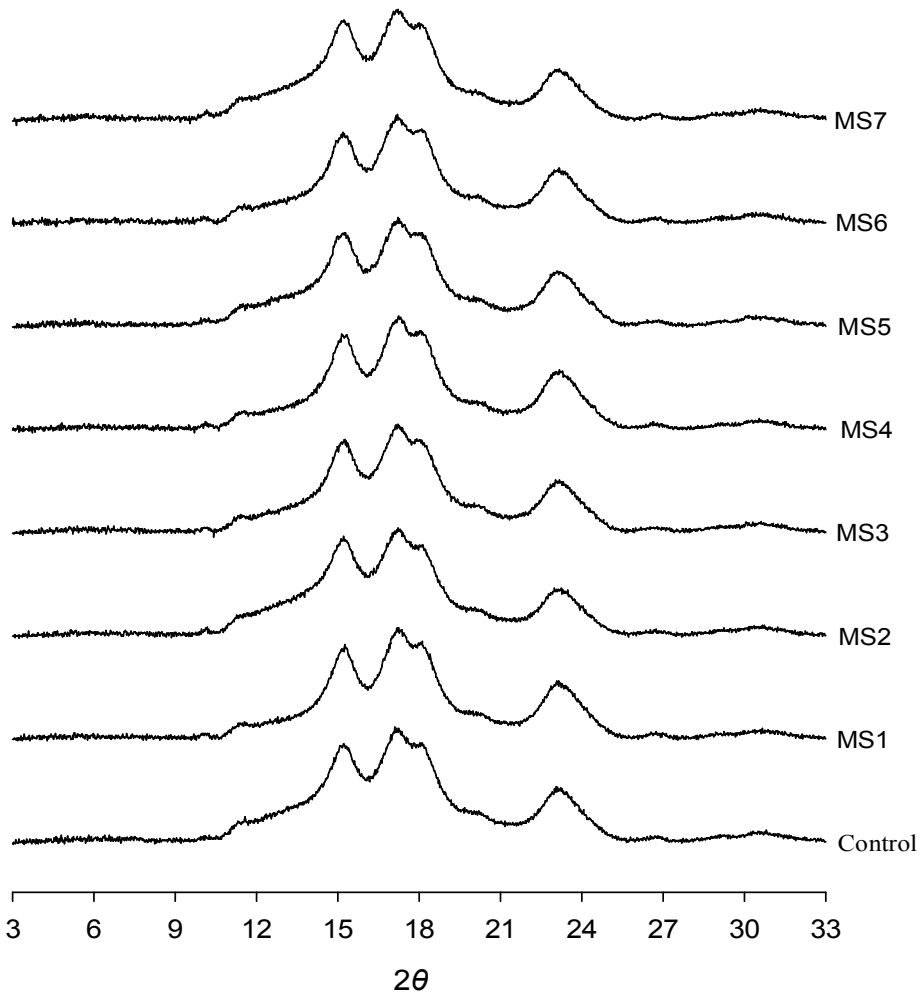

Figure 2. X-ray diffractogram of sweet potato starches. Control and MS1-7 starches showed a typical Ca type.

Table 4. Relative crystallinity of sweet potato starches

Sample[1)]	Relative crystallinity (%)
Control	44.70±0.71[c]
MS1	51.03±1.46[a]
MS2	46.17±1.36[bc]
MS3	48.90±1.61[ab]
MS4	46.07±2.37[bc]
MS5	44.13±0.70[c]
MS6	46.80±2.39[bc]
MS7	47.07±0.58[bc]

[1)] Control = non-irradiated starch; MS1-7 = gamma-irradiated mutant starches.

[2)] The values with different superscripts in the same column are significantly different ($p<0.05$).

5. Thermal properties

When heated with excess water, an order-disorder transition called gelatinization occurs in starch granule (Hoover, 2001). This phase transition initiates in the amorphous regions of the granule, since hydrogen bonding is weaker in these areas than that of crystalline regions (Singh et al., 2003). The gelatinization is associated with many properties of starch, such as granule size, amylose content, distributions of amylopectin chains, crystallinity, and swelling.

The gelatinization parameters such as onset (T_o), peak (T_p), conclusion (T_c) temperatures, temperature range (T_c-T_o), and gelatinization enthalpy (ΔH) examined by DSC are summarized in Table 7. The sweet potato starches used in this study significantly differed in T_o and T_p whereas there was no significant difference in T_c. The gelatinization of the starches was initiated at 68.98-71.60°C, which was similar to other sweet potato starches reported (Baek et al., 2014). Among the starches, MS1 had the highest T_o and T_p values. The differences in gelatinization temperatures could be attributed to the degree of crystallinity. MS1 showed the highest relative crystallinity. This suggests that the crystallites of MS1 had a higher degree of structural stability. The differences in the gelatinization parameters were not attributed to the chain length distribution of amylopectin or to the amylose content

because of the similar values for these factors among the starches. T_c-T_o value represents a degree of crystalline organization (Tester, 1997). However, despite the difference in relative crystallinity, there was no significant difference in T_c-T_o among the starches used in this study. It has been suggested that relative crystallinity is affected by not only crystalline perfection but also different internal structures within granules such as how well the crystallites are oriented towards the incoming X-ray beam (Maaran et al., 2014). ΔH reflects melting of double helical structures in amylopectin-based crystals (Cooke & Gidley, 1992). No difference in ΔH among the starches indicated no difference in the degree of hydrogen bonding in double helices found in all the starches as well as in the magnitude of the thermal energy required to separate amylopectin double helices from their lamellar crystallites during gelatinization.

Table 5. Gelatinization parameters of sweet potato starches

Sample[1)]	T_o[2)] (°C)	T_p (°C)	T_c (°C)	T_c-T_o (°C)	ΔH (J/g)
Control	68.98±0.36^{e}	72.70±0.41^{d}	77.88±0.58^{c}	8.90±0.28^{a}	9.49±0.62^{a}
MS1	71.60±0.08^{a}	74.92±0.18^{a}	79.39±0.12^{a}	7.79±0.04^{b}	10.34±0.06^{a}
MS2	69.01±0.12^{e}	72.80±0.09^{d}	77.91±0.48^{c}	8.89±0.59^{a}	9.89±0.81^{a}
MS3	70.90±0.39^{bc}	74.22±0.23^{b}	78.65±0.23^{abc}	7.75±0.19^{b}	10.35±0.73^{a}
MS4	70.36±0.26^{cd}	74.18±0.04^{b}	79.40±0.30^{a}	9.05±0.55^{a}	9.66±0.35^{a}
MS5	71.31±0.13^{ab}	74.41±0.06^{b}	79.03±0.10^{ab}	7.72±0.04^{b}	10.34±0.12^{a}
MS6	69.88±0.31^{d}	73.49±0.36^{c}	78.34±0.53^{bc}	8.46±0.27^{ab}	9.68±0.32^{a}
MS7	70.56±0.30^{c}	73.65±0.18^{c}	78.35±0.18^{bc}	7.79±0.11^{b}	10.31±0.24^{a}

[1)] Control = non-irradiated starch; MS1-7 = gamma-irradiated mutant starches.

[2)] To = onset temperature, Tp = peak temperature, Tc = conclusion temperature, T_c-T_o = temperature range of gelatinization, ΔH = gelatinization enthalpy.

[3)] The values with different superscripts in the same column are significantly different (p<0.05).

6. Swelling factor

Starch granule swelling is known to begin in the relatively mobile amorphous fractions and in more restrained amorphous regions immediately adjacent to the crystalline regions (Hoover & Manuel, 1996). Swelling apparently is a property of amylopectin. Crystallites within the amylopectin molecules contribute to the onset of swelling and gelatinization (Tester & Morrison, 1990). Amylose acts as both diluent and inhibitor of swelling, especially in the presence of lipids which can form insoluble complexes with some of the amylose during swelling and gelatinization (Leach et al., 1959; Zeleznak & Hoseney, 1987). The starch molecules are held together by hydrogen bonding in the form of crystalline bundles, which are called micelles. The strength and character of the micelle network within the granule is the major factor controlling the swelling behavior of starch (Leach et al., 1959). Therefore, swelling of starch reflects the extent of the associative forces within the granule (Moorthy & Ramanujam, 1986).

Gani et al. (2012) reported a decreased swelling value with an increase in irradiation dose in bean starch samples. Since amylopectin fraction is mainly responsible for swelling (Tester & Morrison, 1990) and therefore a decrease in swelling index may be attributed to a high reduction in amylopectin with irradiation. In contrast, in this study, swelling factor of sweet potato mutant

starches was not in accordance with irradiation. The SF of control and mutant starches in the temperature range between 50 and 80°C is presented in Table 5 and Figure 3. The SF of the sweet potato starches rapidly increased at 60-70°C or 70-80°C depending on the starch sample. Among the starches, MS1 and MS3 showed the lowest SF value at 70°C and 80°C, respectively. SF differences could be influenced by amylose content, amylopectin structure, extent of interaction between starch chains in the native granule, and crystallinity (Sasaki & Matsuki, 1998). The amylose contents and branch chain length distributions of MS1 and MS3 did not differ significantly amongst the sweet potato starches. In the present work, it was found that MS1 and MS3 starches which had the higher relative crystallinity tended to show lower swelling behavior. Similar tendency has also been shown in wheat starches (Lan et al., 2008) and potato starches (Yusuph et al., 2003).

Table 6. Swelling factor of sweet potato starches

Sample[1)]	50°C	60°C	70°C	80°C
Control	1.76±0.22[a]	4.92±0.65[a]	14.43±1.33[a]	16.98±0.09[a]
MS1	1.26±0.31[a]	2.32±0.40[d]	6.13±0.16[e]	14.86±0.61[c]
MS2	1.61±0.37[a]	2.80±0.38[cd]	11.33±0.23[c]	15.38±0.73[bc]
MS3	1.43±0.39[a]	3.07±0.08[bc]	8.22±0.43[d]	12.36±0.21[d]
MS4	1.40±0.41[a]	3.63±0.25[b]	9.36±0.54[d]	16.29±0.75[ab]
MS5	1.36±0.18[a]	2.49±0.53[cd]	8.68±0.54[d]	15.09±0.56[c]
MS6	1.57±0.07[a]	2.68±0.10[cd]	11.74±1.15[bc]	15.57±0.08[bc]
MS7	1.61±0.36[a]	3.10±0.11[bc]	12.73±0.74[b]	14.90±0.83[c]

[1)] Control = non-irradiated starch; MS1-7 = gamma-irradiated mutant starches.

[2)] The values with different superscripts in the same column are significantly different ($p<0.05$).

7. Pasting properties

Pasting occurs after gelatinization in the dissolution of starch and is among the important functional properties of starch in various foods and industrial applications. The pasting characteristics affect food quality such as texture, stability, and digestibility of starch-based product (Brabet et al., 1997). When the pasting begins in starch, the starch granules become very susceptible to shear, resulting in disintegration. The paste, a viscous mass, consists of a continuous phase of solubilized amylose and/or amylopectin and granule remnants embedded in the leached amylose network (Maaran et al., 2014). The pasting properties are mainly contributed by the swollen granules and breakdown of gelatinized starch granules (Han & Hamaker, 2001).

The pasting parameters including peak viscosity (PV), breakdown (BD), final viscosity (FV), setback (SB), peak time, and pasting temperature of sweet potato starches are presented in Table 6.

A decreased trend has been reported in pasting properties with increase in irradiation dose upon direct gamma irradiation of corn starches (Kang et al., 1999; Lee et al., 2006). The decrease in peak viscosity of the modified corn starches is attributed to the formation of low molecular weight molecules due to the degradation of amylopectin (Lee et al., 2006). In this work, control had

the highest PV (2565.67 cP), whereas MS1 had the lowest PV (1812.00 cP). PV can be influenced by friction between swollen granules, relative crystallinity, and extent of amylose leaching. The higher RC and smaller granule size of MS1 was the main causative factor responsible for its lowest PV in this study. BD is caused by disintegration of gelatinized starch granules, and the differences in BD are related to the differences in rigidity and fragility of the swollen granules (Han & Hamaker, 2001). The lower BD (603.50 cP) of MS1 was due to the lower PV. Baek et al. (2014) and Tsakama et al. (2010) also observed a relationship between PV and BD in sweet potato starches, suggesting that starches having high PV are likely to have high BD. Also, the setback (662.00 cP) of MS1 was lower than control and other mutant starches, which could be attributed to the presence of smaller granules embedded in the amylose network in MS1. The peak time of control and mutant starches were not significantly different and were comparable with the starches of other Korean sweet potato varieties reported (Baek et al., 2014; Kim et al., 2013).

Table 7. Pasting parameters of sweet potato starches

Sample[1)]	Viscosity (cP[2)])				Peak time (min)	Pasting temperature (°C)
	Peak	Breakdown	Final	Setback		
Control	2531.50[a]	769.67[ab]	2620.00[ab]	824.00[f]	4.25[ab]	77.48[c]
MS1	1812.00[e]	603.50[c]	1870.50[d]	662.00[g]	4.17[ab]	78.68[a]
MS2	2554.67[a]	755.50[a]	2716.33[a]	951.67[d]	4.31[a]	77.93[bc]
MS3	2164.52[cd]	613.50[c]	2584.64[b]	1048.67[a]	4.27[ab]	78.47[ab]
MS4	2394.00[b]	761.50[ab]	2625.50[ab]	993.00[c]	4.24[ab]	78.75[a]
MS5	2304.50[b]	678.50[bc]	2652.00[ab]	1026.00[b]	4.20[ab]	78.75[a]
MS6	2167.13[c]	639.25[c]	2474.13[ab]	946.25[c]	4.14[ab]	78.33[bc]
MS7	2042.50[d]	639.75[c]	2302.00[c]	899.25[e]	4.09[b]	78.70[a]

[1)] Control = non-irradiated starch; MS1-7 = gamma-irradiated mutant starches.

[2)] cP = centipoise

[3)] The values with different superscripts in the same column are significantly different (p<0.05).

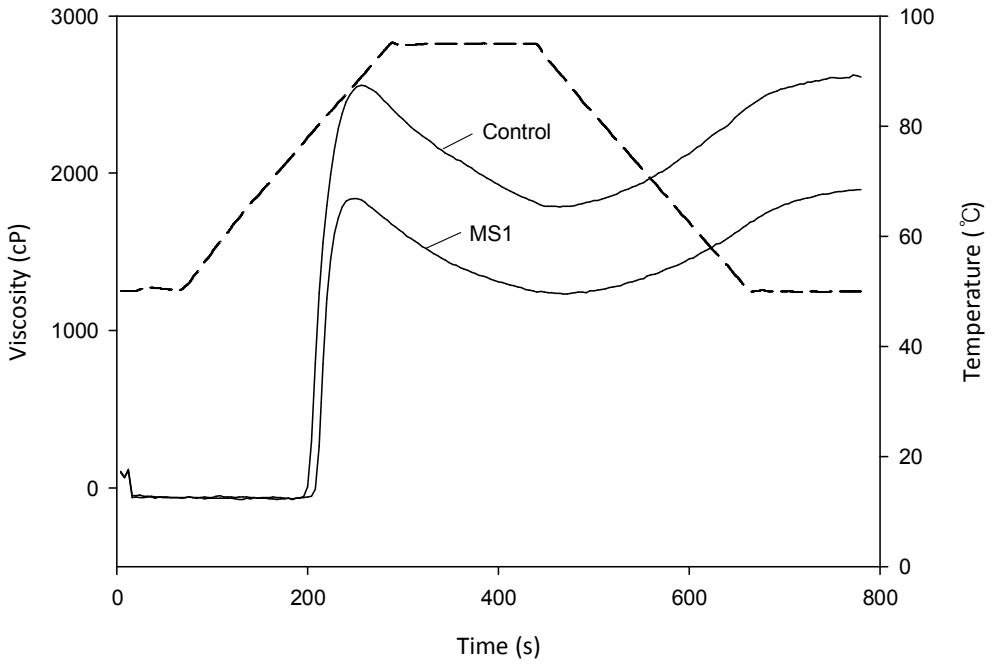

Figure 3. RVA viscograms of control and MS1 starches. Solid line, viscosity; Dashed line, temperature.

8. Rheological properties

It is necessary to understand the rheological properties of starch, since the rheological characteristics determine the usage in food products. During gelatinization, starch granules swell to several times their initial volume. The gelatinized starch recrystallizes during storage in a process known as retrogradation, which is the reassociation of amylose and amylopectin to form double helices and crystalline structures (Steeneken, 1989). These changes are responsible for the rheological characteristics exhibited by starch suspensions during heating and shearing. Dynamic rheometry provides useful information for understanding the textural change of retrogradation potency and allows continuous measurement of dynamic moduli during temperature and frequency sweep testing of a starch suspension (Lin et al., 2013; Singh et al., 2007). The parameters of storage modulus (G'; solid component of the network, related to elastic energy) and loss modulus (G''; liquid component, related to viscous flow) were obtained in the frequency range of 0.1 to 10 Hz. The dynamic frequency sweep for the sweet potato starches are illustrated in Figure 5. The G' and G'' of all the starches increased with increasing angular frequency, but the G' was greatly higher than the G'', a characteristic of gel, showing solid-like behavior (Clark & Ross-Murphy, 1987). In general, amylose retrogradation occurs on cooling

and very short-term aging (C. Biliaderis & J. Zawistowiski, 1990; Doublier & Choplin, 1989), while amylopectin retrogradation proceeds slowly during aging and requires several weeks or months of storage for equilibrium (C. G. Biliaderis & J. Zawistowiski, 1990; Miles et al., 1985). The gel formation in this report was dependent on the short-term starch retrogradation of amylose. MS1 showed the lower viscoelastic behavior than the other starches. One possible reason for this result was the lower interaction between leached amylose chains of MS1, resulting in weaker amylose network formation during the cooling. It was also found in the result of pasting properties that MS1 had the lower setback value than the other starches (Table 6).

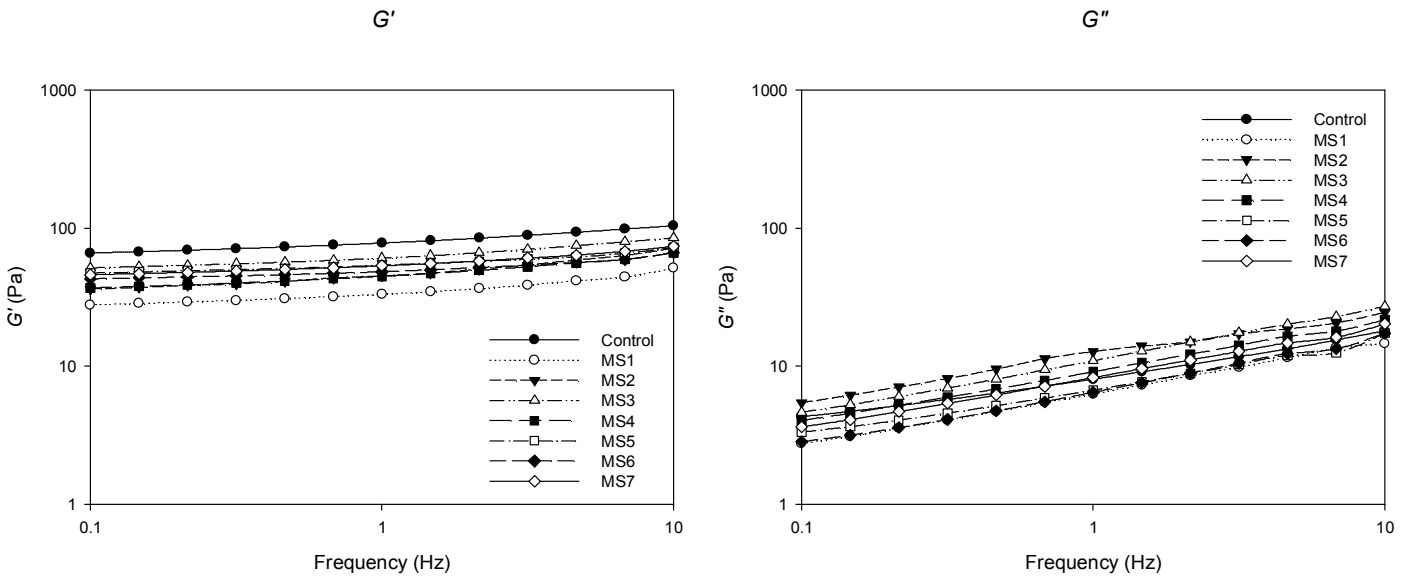

Figure 4. Frequency sweep showing *G'* and *G"* for gels of sweet potato starches.

9. Starch digestibility

Starch and starchy food products can be classified according to their digestibility, which is characterized by the rate and the duration of the glycemic response (Singh et al., 2010). Starch generally contains a portion that digests rapidly (rapidly digestible starch, RDS), a portion that digests slowly but completely in the small intestine (slowly digestible starch, SDS) and a portion that is not hydrolyzed by the enzymes in the small intestine and passes to the large intestine (resistant starch, RS) (Englyst et al., 1992). Both SDS and RS are correlated with a low glycemic index (Englyst et al., 1996). SDS offers the advantage of a slow increase of postprandial blood glucose levels and sustained blood glucose levels over time compared with RDS (Lehmann & Robin, 2007). SDS also can have implications for physical and mental performance, satiety, and diabetes management (Wolf et al., 1999). RS fractions is fermented in the large intestine by human colonic microflora to short-chain fatty acids such as acetate, propionate, and butyrate (Englyst et al., 1996; Topping & Clifton, 2001). The products of fermentation are effective for preventing colorectal cancer, cardiovascular disorder, and metabolic and inflammatory bowel diseases such as diabetes and diverticulitis (Van Hung et al., 2015).

In general, once starch underwent direct gamma irradiation, an digestibility increase is induced by structural degradations in both granules and molecules of starch (Yoon et al., 2010). Gamma irradiation decreases SDS contents in waxy, normal, and high-amylose corn starches, suggesting that SDS may be partially transformed to RS by the irradiation (Lee et al., 2013; Yoon et al., 2010). It is assumed that free radicals produced by the irradiation induce chain associations resulting in the formation of more stable structures which causes hindrance to enable effective enzymes attack on starch (Chung et al., 2010; Lee et al., 2013). However, all the raw sweet potato mutant starches used in this study had lower RDS contents in comparison with their SDS contents, indicating the advantage of a slow increase in postprandial blood glucose levels (Lehmann & Robin, 2007). The contents of RDS, SDS, and RS of the raw and cooked sweet potato starches are presented in Table 8. The mutant starches had significantly lower RDS contents (4.81-6.76%) than that of control (8.75%) except for MS2. Among the raw starches, MS1 showed the lowest RDS content accompanied by a corresponding increase of RS content. The digestibility of native starches has been attributed to the interplay of many factors including granule size, extent of molecular association between starch chains, amylose/amylopectin ratio, branch chain length distribution of amylopectin, degree of crystallinity,

cracks on the granule surface, channels within the granules, and the presence of lipid-amylose complexes (Goñi et al., 1997; Goddard et al., 1984; Hoover & Zhou, 2003; Zhang et al., 2006). In general, starch granule size has a negative relationship with digestibility. Lindeboom et al. (2004) observed that the small barley and wheat starch granules hydrolyze faster than the large granules. However, the digestibility of MS1 raw starch was not associated with smaller granule size (Table 1). Also, the decrease in RDS of MS1 raw starch was not attributed to the amylose/amylopectin ratio (Table 2) and the branch chain length distribution of amylopectin (Table 3). The difference in digestibility of MS1 was probably due to the higher relative crystallinity (Table 4) and/or stronger molecular association between starch chains than other starches.

When starch is used for manufacturing food products, starch may undergo a cooking process, which increases the rate of hydrolysis by gelatinizing the starch and makes it more easily available for enzymatic access (Singh et al., 2010). After the sweet potato starches were cooked, the RDS contents of the cooked starches increased by 57.60-70.55% and the SDS and RS fractions decreased by 6.68-26.52% and 43.24-50.92%, respectively. MS1 had the lowest content of RDS and the highest content of SDS among the starches, whereas the digestibilities of other mutant starches were not significantly

different compared to the control. When starch is gelatinized, the crystalline region is destroyed and water molecules become linked by hydrogen bonding to the exposed hydroxyl groups of amylose and amylopectin, causing an increase in granule swelling and solubility (Singh et al., 2010). Therefore, the extent of starch digestibility through enzymatic hydrolysis can be determined by the water activity or the availability of water. The lower digestibility of cooked MS1 starch was most likely caused by the lower swelling behavior resulting in relatively less area to which the enzyme is accessible.

Table 8. Contents of RDS, SDS, and RS in raw and cooked sweet potato starches

Sample[1)]	Raw starch			Cooked starch		
	RDS (%)	SDS (%)	RS (%)	RDS (%)	SDS (%)	RS (%)
Control	8.75±0.49^{a}	31.95±2.92^{cd}	59.30±3.22^{bcd}	73.50±1.50^{a}	10.72±2.54^{b}	15.78±2.83^{a}
MS1	4.82±0.26^{d}	31.63±0.65^{cd}	63.55±0.69^{a}	63.12±1.75^{b}	25.53±2.79^{a}	11.35±2.60^{a}
MS2	8.13±0.69^{a}	34.67±0.43^{abc}	57.20±0.61^{d}	73.98±1.86^{a}	12.31±2.22^{b}	13.71±0.43^{a}
MS3	6.76± 0.23^{b}	34.93±1.63^{ab}	58.31±1.61^{bcd}	75.40±1.89^{a}	11.48±3.10^{b}	13.12±2.27^{a}
MS4	5.67±0.45^{cd}	34.45±1.85^{abcd}	59.88±2.07^{bcd}	75.08±1.84^{a}	9.61±1.46^{b}	15.31±0.91^{a}
MS5	5.20±0.34^{d}	33.53±1.13^{bcd}	61.26±0.79^{ab}	75.09±3.061^{a}	10.37±2.01^{b}	14.54±2.37^{a}
MS6	6.31±1.06^{bc}	33.10±0.84^{bcd}	60.58±0.23^{bc}	76.08±1.86^{a}	11.14±1.33^{b}	12.77±1.73^{a}
MS7	5.35±0.47^{cd}	36.64±0.68^{a}	58.01±0.75^{cd}	75.58±1.01^{a}	10.61±1.31^{b}	13.81±0.36^{a}

[1)] Control = non-irradiated starch; MS1-7 = gamma-irradiated mutant starches.

[2)] RDS = rapidly digestible starch, SDS = slowly digestible starch, RS = resistant starch.

[3)] The values with different superscripts in the same column are significantly different (p<0.05).

CONCLUSION

Mutant starches from gamma irradiated sweet potato were examined in this study to characterize physicochemical, pasting, and digestion properties and evaluate the potential applicability in food industry. Three mutant lines (MS1, MS4 and MS7) had the higher crop yields than the control line. Among the mutant starches, MS1 had significant differences in properties of starch. MS1 had the smaller granule size and higher relative crystallinity, indicating the changes in activity of enzymes related to starch biosynthesis by gamma irradiation. There were significant differences in the gel properties of MS1 from the control. MS1 showed the lower pasting and viscoelastic behaviors, indicating that the starch had the characteristics of a weak gel. In addition, MS1 had lower digestibility in both raw and cooked starches. Therefore, the mutant starch may have potential as an ingredient for health functional foods and improves eating quality (softer mouthfeel).

In short, gamma irradiation is a useful method for a better breeding performance related to plant yields and producing a new cultivar which has different characteristics of starch.

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국문초록

돌연변이 육종 방법의 하나로서 감마선 조사는 작물의 수확량 증가나 새로운 특성을 갖는 품종을 개발하기 위하여 사용된다. 이 연구에서는 한국산 고구마 품종인 신건미 줄기에 ^{60}Co 감마선을 시간당 5 Gy 의 속도로 총 0.1 kGy 를 조사하여 돌연변이를 유발하였으며, 이러한 돌연변이 품종에서 전분을 분리하여 이화학적, 페이스팅 및 소화 특성을 알아봄으로써 이의 식품학적 가치를 평가하였다. 7 개의 돌연변이 품종을 실험에 사용하였고, 100g 이상의 괴근 비율은 대조구와 돌연변이(MS1-7)가 각각 44.71, 52.94, 46.44, 38.80, 52.81, 32.12, 25.90, 50.41%로 MS1, MS4, MS7 이 대조구보다 높은 수확량을 나타내었다.

전분 입자의 평균체적직경($d_{4,3}$)은 12.98-43.91 μm 의 넓은 범위를 보였으며 입자 형태에는 변화가 없었다. 아밀로스 함량과 아밀로펙틴의 가지 사슬 길이는 시료간의 유의적인 차이가 나타나지 않았다. 모든 전분은 C_a 형의 X-선 회절 양상을 보였고, 상대적 결정화도는 MS1 이 가장 높은 값을 가졌다. 이러한 높은 결정화도와 구조적 안정성으로 인해 MS1 의 호화개시온도 (T_o)와

호화정점온도 (T_p)가 가장 높았다. MS1 의 낮은 팽윤력과 작은 입자크기에 의해 신속점도측정을 측정하였을 때 MS1 이 가장 낮은 값을 보였다. 점탄성 측정 결과에서, MS1 의 가장 낮은 저장계수(G')는 호화 과정에서 용출된 아밀로스 간의 약한 상호작용 때문이며 이는 낮은 치반점도 결과에서도 증명되었다. 생전분과 호화전분의 소화율에서는 MS1 이 대조구와 다른 돌연변이 전분들보다 낮은 속소화성전분(RDS) 함유량이 적고 지소화성전분(SDS) 또는 저항전분(RS) 함유량이 많아 낮은 소화 특성을 나타내었다.

결론적으로, 감마선 조사로 돌연변이를 유발한 고구마 품종에서 대조구보다 높은 수확량과 다른 특성을 갖는 전분을 확인함으로써 감마선 조사의 작물학적 유용성과 돌연변이 전분의 새로운 식품학적 이용가능성을 제시하였다.

주요어: 고구마, 감마선 조사, 돌연변이 전분, 이화학적 특성, 소화율

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