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RESEARCH ARTICLE

Comparison of Physicochemical Properties of Starches and Parenchyma Cells Isolated from Potatoes Cultivated in Korea

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Abstract Potato starches (ST) and parenchyma cells (PC) were isolated from Atlantic and Superior potatoes cultivated in Korea, and their morphology, chemical composition, crystal packing arrangement, solubility, swelling power, gelatinization, pasting viscosity, and *in vitro* digestibility were investigated. PC was tightly wrapped around different numbers of ST granules and, in the dehydrated state, formed multi-PC aggregates that dispersed in an aqueous medium into individual PC. Relative to ST, solubilities (determined by soluble solid contents) were higher for PC, while the opposite trends in starch leachate contents were observed. PC exhibited lower swelling powers, higher gelatinization temperatures, and lower pasting viscosities. Uncooked PC exhibited more resistance to amylolytic enzyme attack, while cooked PC was rapidly hydrolyzed. Due to the presence of intact PC walls, dehydrated PC showed different physicochemical properties, compared to ST granules.

Keywords: potato, potato parenchyma cell, potato starch, physicochemical properties

Introduction

Potato (*Solanum tuberosum* L.) possesses abundant carbohydrates (starch and non-starch polysaccharides) and proteins (comprised of relatively rich essential amino acids) (1). Relative to other starchy crops (rice, corn, and wheat), potato contains more vitamins (C and B complex), minerals (potassium, magnesium, calcium, phosphorus, and iron), and bioactive components (carotenoids, anthocyanins, and polyphenolic compounds) (2). Thus, potato has been one of the most important staple foods for humans for many years.

Fresh potatoes have been widely consumed as the individual products, the canned and frozen products, and the raw materials for dehydrated potato products (potato starch, flour, flake, dice, and granules) (3). However, cooked potatoes and potato-based foods, subjected to boiling, par-boiling, deep-fat frying, or baking treatment, are categorized as high glycemic index (GI) foods (4), which have recently exhibited a trend of their reduced consumption. Apart from issues relating to a high GI, the use of potato starches, flours, and granules as food ingredients is confined to potato-based products (reconstructed French fries, potato chips, potato snacks, and instant soup pre-mixes) (5). Limited use of dehydrated potato products is due to a rapid settling characteristic, dramatic viscosity development, and formation of a sticky potato starch paste in dehydrated potato materials.

The current industrial demands require moderation of processing applications, and the concerns on rapid and easy digestion of dehydrated potato products remain a problem. Therefore, several recent studies have been conducted for development of new types of dehydrated potato products (5-7) to address these concerns, based on the common concept of individual separation of intact parenchyma cells (comprising inner potato tissues) from potato whole tissues. Anantachote (6) developed separation methods of individual parenchyma cells from raw (uncooked) potato whole tissues using pectinase and alkaline (containing a chelating agent). Kim and Kim (7) separated and characterized parenchyma cells from cooked whole tissues of Atlantic

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and Superior potatoes cultivated in Korea using pectinase. More recently, Kim and Kim (5) prepared dehydrated parenchyma cells and flour from raw (uncooked) and cooked whole tissues of Dubaek potatoes cultivated in Korean, and compared physicochemical properties. Overall, ungelatinized and retrograded potato starches were trapped in intact parenchyma cells, despite their exposure to the outer environment in potato flour (5-7). These studies suggested that differences in physicochemical properties between dehydrated parenchyma cells and potato flours may be due to the presence of intact parenchyma cells (5-7). However, the studies failed to provide characteristics of individually separated parenchyma cells due to a low purity resulting from incorporation of free starch granules and ruptured, empty parenchyma cells. Also, the information on the digestibility of parenchyma cells in uncooked and cooked states was less available. The objective of this study was to investigate and compare the physicochemical properties and *in vitro* digestibility of the highly pure, individual parenchyma cells (including ungelatinized starch granules) and the starches isolated from Superior and Atlantic potatoes to understand the impact of the intact parenchyma cell wall on characteristics of potato parenchyma cells.

Materials and Methods

Materials Potatoes from Atlantic and Superior cultivars were used for preparation of both potato parenchyma cells and starches. Potatoes, harvested in July, 2013 from a farm near Pyeongchang, Korea, and stored at 4°C for 2 weeks, were obtained from Dr. Se-Jin Hong of the Department of Plant Science, Gangneung-Wonju National University, Gangneung, Korea, and stored at 4°C and 90-95% relative humidity during preparation of potato parenchyma cells and starches. Preparation of potato parenchyma cells and starches was completed within 1 month for minimization of starch loss due to low temperature sweetening. Pectinase (rich in endo-polygalacturonase from *Aspergillus niger*) and Congo red were purchased from Sigma-Aldrich Co. (St. Louis, MO, USA). A total starch assay kit (K-TSTA) was purchased from Megazyme International Ltd. (Wicklow, Ireland). All chemicals and reagents were of analytical grade.

Isolation of starch granules from potatoes Potato starch (ST) was isolated from raw potatoes following the method outlined by Kim and Kim (5). Potatoes (1 kg, wb or wet weight basis) were washed, peeled, and sliced to 1 cm in thickness, then slices were soaked in an aqueous solution (1 L) of 0.1% (w/v) sodium bisulfite. Potato slices were ground using a mixer (HMF-552; Hanil Electric, Seoul, Korea), then passed through a 140 mesh standard sieve (pore size=106 μm). The resulting filtrate was kept at 4°C for 4 h, after which the supernatant was discarded. The resulting precipitate was re-suspended using deionized water (DIW, 1 L). The procedure from starch precipitation to re-suspension was carried out 4 times. The resulting ST cake of the final step was suspended in ethanol (95%, 500 mL), stirred for 10 min, and recovered using vacuum filtration on a Büchner funnel. The resultant ST was dried at 45°C for 48 h, and stored in a Teflon bottle at room temperature (approximately 24°C).

Separation of parenchyma cells from raw potato whole tissues Potato parenchyma cells (PC) were separated from raw (uncooked) potato whole tissues following the method of Kim and Kim (5). Potatoes were washed, peeled, cut into cubes (1×1×1 cm), and washed with DIW to remove ST granules on the surface of the cubes. Pectinase (110 mg, 0.5 U/mL) was added to 350 mL of 100 mM citrate buffer (pH 2.5), and incubated at 50°C for 30 min after which potato cubes (75 g, wb) and ascorbic acid (400 ppm) were added to the reaction medium. The resulting mixture was then incubated at 50°C for 3 h under continuous stirring (100 rpm), after which the mixture was passed through a series of 20 and 140 mesh standard sieves. Separated PC was defined as a sieve overs on a 140 mesh standard sieve through a 20 mesh standard sieve. PC was washed with DIW for removal of both free starch granules and broken walls of PC, then dispersed in ethanol (95%), stirred with a spatula, and held at room temperature (24°C) for 30 min for settling of solid particles. The supernatant was then discarded. This series of dehydration steps, including PC dispersion, stirring, settling, and supernatant removal, was repeated a total of 3 times. Dehydrated PC after the final step was recovered using vacuum filtration on a Büchner funnel, dried at room temperature, and stored in a Teflon bottle at room temperature.

Microscopy The morphological characteristics of ST and PC from Superior and Atlantic potatoes were viewed under a field emission scanning electron microscope (FE-SEM, JSM-6700F; Jeol Ltd., Tokyo, Japan) following the method of Kim and Kim (5). PC was further observed under an inverted light microscope (LM, BX40; Olympus Corporation, Tokyo, Japan) at 40× magnification. For LM observation, PC was stained with Congo red (specific to cellulosic materials) or with Congo red and iodine only for PC pastes, following the method outlined by Kim and Kim (7).

Chemical compositions The moisture, protein (%N×6.25), lipid, and ash contents of PC and ST were determined following AACC Methods 44-19 (8), 46-08 (9), 08-01 (10), and 30-26 (11), respectively. The carbohydrate content was calculated as subtraction of the sum of protein, lipid,

and ash contents (%, db or dry weight basis) from 100. Total starch contents of PC were assayed using a total starch assay kit, following AACC method 76-13 (12). Apparent amylose and phosphorus contents of PC and ST were determined using a colorimetric method (13) and using inductively coupled plasma-atomic emission spectroscopy (ICP-AEC) (14), respectively.

X-ray diffraction (XRD) XRD patterns of PC and ST (14.8% moisture content) were investigated using an X-ray diffractometer (D8 Advance; Bruker AXS GmbH, Karlsruhe, Germany) as outlined by Cheetham and Tao (15). The relative crystallinity was defined as the percent (%) ratio of the sum of total crystalline peak areas to the sum of a total diffractogram.

Solubility and swelling power The swelling powers of PC and ST were measured at 25, 40, 55, 70, and 85°C, following the method outlined by Kim and Kim (5). Soluble solid and starch leachate contents were determined using supernatants recovered from measurement of the swelling power, according to the methods of Choi *et al.* (16) and Chrastil (17), respectively.

Differential scanning calorimetry (DSC) Gelatinization properties of PC and ST were investigated using a differential scanning calorimeter (DSC S-650; Scinco, Daejon, Korea). PC or ST (5 mg, db) was directly weighed into a stainless steel pan, and DIW was added to a total weight of 20 mg. The pan was hermetically sealed, equilibrated for 24 h at room temperature (24°C), and then scanned at a heating rate of 10°C/min from 25 to 120°C. A sealed, empty pan was used as a reference.

Pasting viscosity Pasting viscosity profiles of PC and ST were investigated using a Rapid Visco Analyzer (RVA-3D; Newport Scientific, NSW, Australia). PC (2.25 g, db) and ST (1.5 g, db) were directly weighed into aluminum canisters, followed by addition of DIW to a total weight of 28 g. PC and ST samples were analyzed at a constant rotation speed of 160 rpm of a plastic paddle following a programmed heating profile of holding at 50°C for 1 min, heating from 50 to 95°C at a heating rate of 12°C/min, holding at 95°C for 2.5 min, cooling to 50°C at a cooling rate of 12°C/min, and holding at 50°C for 2 min.

***In vitro* starch digestibility** The *in vitro* starch digestibility for uncooked PC and ST was determined following the method outlined by Englyst *et al.* (18) with modification. Porcine pancreatic α-amylase (0.45 g) was dispersed in water (4 mL), and centrifuged at 1,000×*g* for 10 min. The supernatant (2.7 mL) was transferred to a beaker, and amyloglucosidase (0.3 mL) was added. This enzyme solution was freshly prepared for each digestion. PC or ST (100 mg, db) were mixed with 4 mL of 0.5 M sodium acetate buffer (pH 5.2) in 50 mL conical tubes. The enzyme solution (1 mL) and 15 glass beads (4 mm diameter) were added to each tube. Mixtures were incubated in a shaking water bath at 37°C with 200 strokes/min. Aliquots (0.1 mL) were taken at intervals of enzymatic hydrolysis, and immediately mixed with 1 mL of 80% (v/v) ethanol. The released glucose content was measured using a glucose oxidase-peroxidase (GOPOD) reagent. For gelatinized PC and ST, ST or PC (100 mg, db) was mixed with DIW (2 mL) in 50 mL conical tubes that were capped and the contents were vertexed for 1 min. The tubes were then heated in a boiling water bath for 20 min with gentle magnetic stirring. After heating, tubes were placed in a water bath at 37°C to equilibrate for 10 min. The same procedures for digestibility were followed.

Statistical analysis All measurements were repeated at least twice for analysis of PC and ST. All experimental data were expressed as means±standard deviation (SD), and subjected to an analysis of variance (ANOVA). Significant differences among potato components were analyzed using a least significance difference (LSD) test. Significance for all testing was defined as $p<0.05$. All statistical computations and analyses were conducted using SAS software (version 8.02; SAS Institute, Inc., Cary, NC, USA).

Results and Discussion

Morphology Morphological characteristics of ST and PC isolated from Atlantic and Superior potatoes were observed using FE-SEM and LM (only for PC) (Fig. 1). Both Atlantic and Superior ST exhibited oval and elliptical morphologies with granule sizes of 2-100 μm (Fig. 1A and B), in agreement with previous reports (5,6). Both Atlantic and Superior PC surrounded ST granules, in agreement with Kim and Kim (5) and Anantachote (6) (Fig. 1C and D). Multi-PC aggregates of several individual PC granules stuck together were frequently observed (Fig. 1C and D). Nevertheless, the morphological structures of PC obtained in this study were consistent with structures of potato PC separated using pectinase (5-7) and an acid/alkaline treatment (6,19) from raw (uncooked) and cooked potatoes.

To verify whether the multi-PC aggregates could be present to individual PCs in the aqueous medium and whether the broken/ruptured PCs and free ST granules were present, dehydrated PC dispersed with DIW were stained with an aqueous solution of Congo red (specific to cellulose lamellae), followed by LM observation. Congo red highlighted intact and damaged PC wall components as a red color (Fig. 1E and F). Similar to observation under

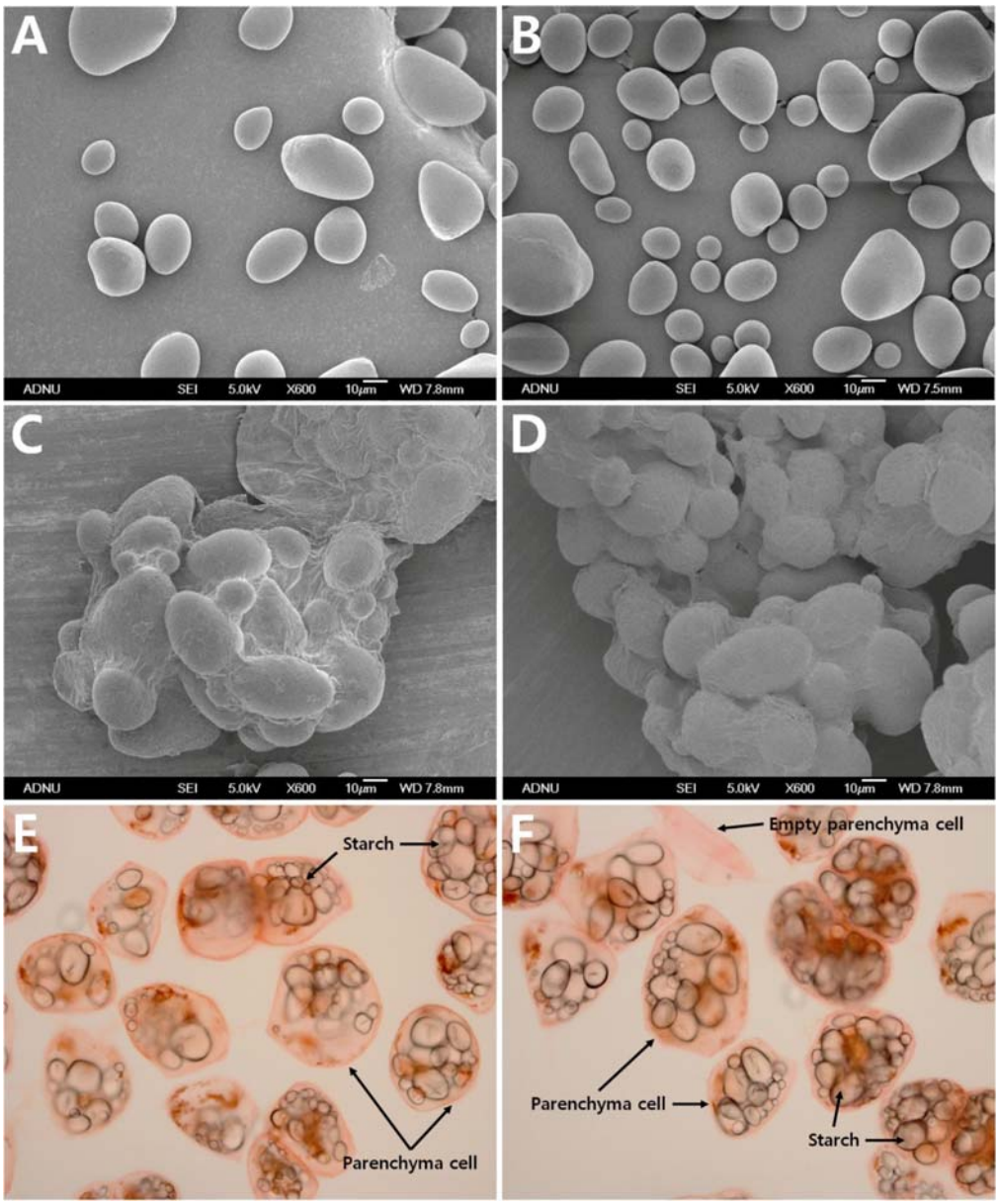

Fig. 1. FE-SEM (A-D) and LM (E,F) images of starches (A,B) and parenchyma cells (C-F) isolated from Atlantic (A,C,E) and Superior (B,D,F) potatoes.

FE-SEM (Fig. 1C and D), ST granules were entrapped in PC to different degrees. In the hydrated state, PC exhibited roughly spherical shapes and were individually dispersed (Fig. 1C and D), in agreement with previous reports (5,6,19). Moreover, almost all separated PC were intact, and free ST granules that were released from damaged/ruptured PC were rarely observed, although empty PC was often observed (Fig. 1E and F). Consequently, the PC separation conditions used in this study should be appropriate for preparation of highly pure, intact PC from potato whole-tissues. Overall, the morphological characteristics of ST and PC did not differ between Atlantic and Superior potatoes.

Chemical compositions Protein, lipid, ash, and total carbohydrate contents of Atlantic and Superior ST were 0.5, 0.1, 0.3-0.4, and 99.0-99.2%, respectively, similar to previously reported values of potato starch (Table 1) (5,6,20). Atlantic and Superior PC contained 3.9-4.8% of protein, 0.1-0.2% of lipids, 0.3-0.4% of ash, and 94.6-95.6% of total carbohydrates (Table 1). The protein and ash contents of PC reported herein were less than protein (10.2-11.5%) and ash (3.8-4.1%) contents of Atlantic and Superior potato flours reported previously (7), probably due to non-recovery of proteins and ash partially dissolved and/or leached from potato whole tissues during pectinase treatment in the reaction medium, as suggested by Kim and

Table 1. Mean[1] values for chemical compositions of starches (ST) and parenchyma cells (PC) isolated from Atlantic and Superior potatoes

Cultivar	Potato material	Protein (%, db)	Lipid (%, db)	Ash (%, db)	TC[2] (%, db)	TS[3] (%, db)	NSP[4] (%, db)	AM[5] (%, db)	Phosphorus (mg%, db)
Atlantic	ST	0.5±0.0^{c}	0.1±0.0^{a}	0.4±0.0^{ab}	99.0±0.0^{a}	-	-	28.0±0.0^{a}	105.6±0.5^{a}
	PC	4.8±0.2^{a}	0.1±0.0^{a}	0.5±0.0^{a}	94.6±0.1^{c}	85.8±0.3^{b}	8.8±0.3^{a}	20.8±0.2^{c}	97.0±0.6^{b}
Superior	ST	0.5±0.1^{c}	0.1±0.0^{a}	0.3±0.0^{c}	99.2±0.1^{a}	-	-	26.9±0.1^{b}	55.3±0.3^{c}
	PC	3.9±0.1^{b}	0.2±0.0^{a}	0.3±0.0^{bc}	95.6±0.1^{b}	87.4±0.8^{a}	8.2±0.5^{a}	19.7±0.0^{d}	51.0±1.1^{d}

[1]Mean values of duplicate measurements; Values sharing the same uppercase letters within columns are not significantly different (p<0.05).
[2]TC; Total carbohydrate (%)=100-(protein+lipid+ash)
[3]TS; Total starch
[4]NSP; Non-starch polysaccharide
[5]AM; Amylose content

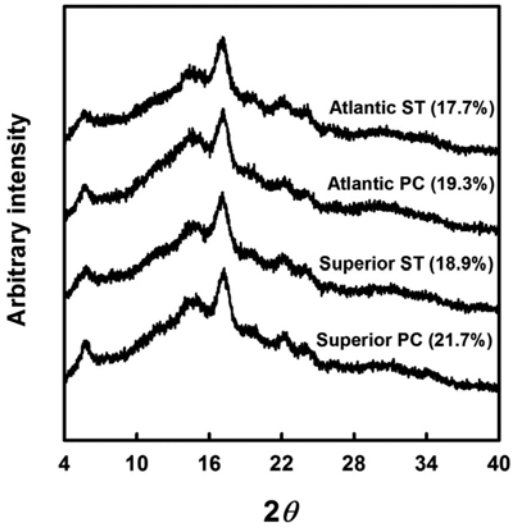

Fig. 2. XRD patterns of starches (ST) and parenchyma cells (PC) isolated from Atlantic and Superior potatoes. A mean value in parenthesis refers to the relative crystallinity.

Kim (5) and Anantachote (6). For PC, the total starch contents were significantly (p<0.05) higher for the Superior cultivar (87.4%) than for the Atlantic cultivar (85.8%) (Table 1). The lower total starch contents of Atlantic PC were probably due to differences between cultivars. Nevertheless, differences in phosphorous contents may not be excluded, because phosphate groups esterified onto the amylopectins of potato starches can restrict the action of amyloglucosidase (an amylolytic enzyme used in the total starch assay) on starch molecules.

Based on total carbohydrate (TC) and starch (TS) contents, the non-starch polysaccharide contents (TC-TC) of PC were 8.8% and 8.2% for Atlantic and Superior cultivars, respectively (Table 1). The amylose and phosphorus contents were significantly (p<0.05) higher for Atlantic and Superior ST, compared with PC. As reported by Kim and Kim (5), the amylose and phosphorus contents appeared to be affected by the starch contents of ST and PC. Meanwhile, Atlantic ST and PC exhibited significantly (p<0.05) higher amylose and phosphorus contents than Superior ST and PC (Table 1), which indicated different physical properties between Atlantic and Superior cultivars in potato materials. The amylose and phosphorus contents are known to be a main factor affecting the solubility, swelling power, gelatinization, pasting viscosity, and paste clarity of potato starches (1).

X-ray diffraction (XRD) The crystal packing arrangements of ST and PC isolated from Atlantic and Superior potatoes were investigated using an X-ray diffractometer (Fig. 2). Both ST and PC for both potato cultivars exhibited a typical B-type crystal packing arrangement with intense peaks at 5.8°, 14.8°, 17°, and 23-25° 2θ (21). The relative crystallinity was higher for Superior ST, and similar patterns in relative crystallinity were observed for PC (Fig. 2). The amylose contents of starches are known to be negatively correlated to their relative crystallinities (15). Phosphate monoesters within potato ST may prevent formation of crystalline structures, although the predominant impact on the restriction of crystal formation may be due to the amylose content (21). Thus, the results reported herein were due to higher amylose and phosphorus contents of Atlantic ST and PC (Table 1).

Based on XRD patterns of ST and PC, the peaks of PC were intense at 5.8° and 17° 2θ, and its intensity of the X-ray signal was higher in a range of 6.0-16° 2θ (Fig. 2). Thus, a higher relative crystallinity was obtained for PC, perhaps due to the presence of wall components of PC comprised of cellulose and hemicellulose (Fig. 1E and F). Intense peaks at 6.7°, 7.4°, 10.2°, and 16° 2θ were observed for microcrystalline cellulose (22). Accordingly, the increase in the relative crystallinity of PC might be related to intensities of X-ray signals obtained from crystalline structures present in wall components of PC that added to signals from ST.

Solubility and swelling power The solubility of ST and PC isolated from Atlantic and Superior potatoes were determined as soluble solids and ST leachate contents in

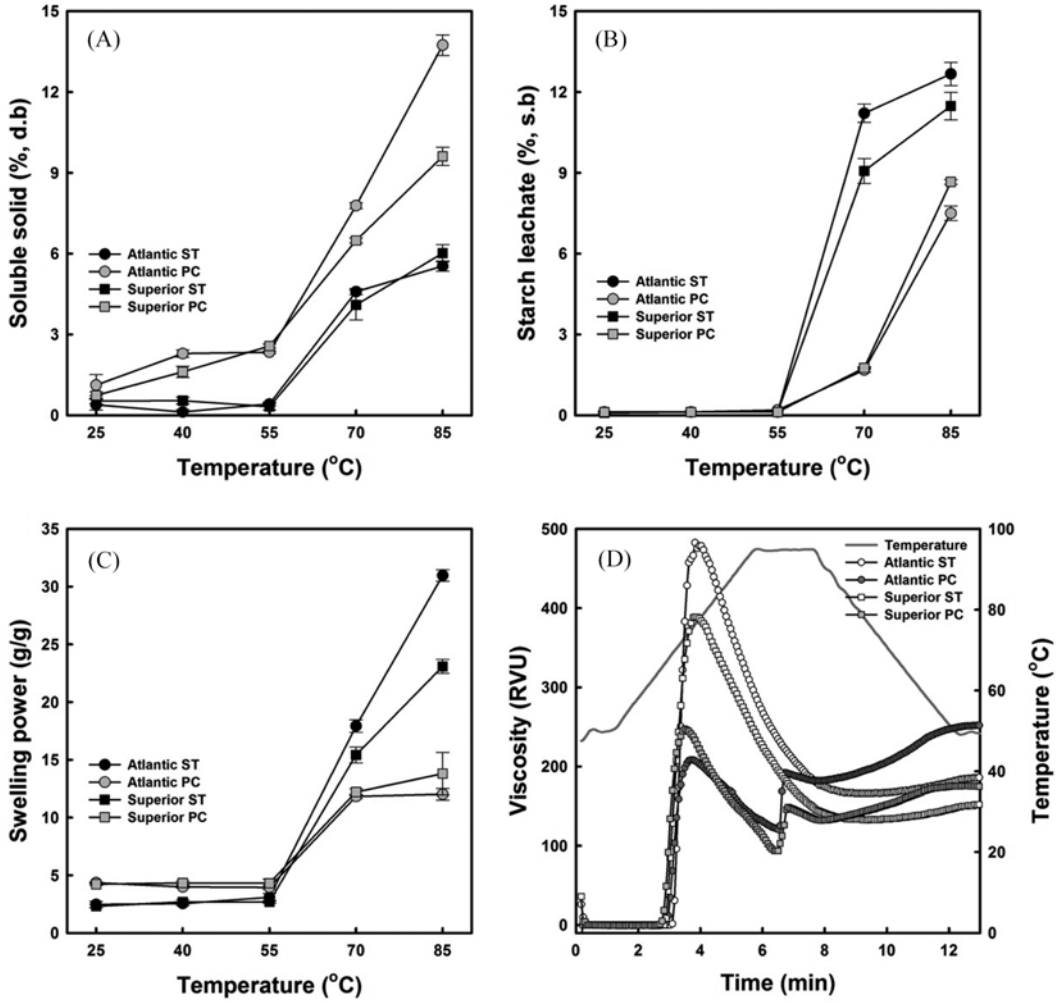

Fig. 3. Soluble solid (A), starch leachate (B), swelling power (C), and pasting viscosity profile (D) of starches (ST) and parenchyma cells (PC) isolated from Atlantic and Superior potatoes.

supernatants recovered during swelling power analysis (Fig. 3A and B). Based on soluble solid contents, regardless of the potato cultivar, the solubility of PC sharply increased from 55°C after its gradual increase in the temperature range of 25-55°C, while ST solubility began to increase at 55°C (Fig. 3A). Also, PC exhibited higher solubility than ST at all temperatures in this study, perhaps due to the presence of soluble components (protein, ash, hemicellulose, and pectin) as well as ST molecules leached from ST granules in PC. Based on ST molecules leached from ST granules (Fig. 3B), the amount of ST leachate started increasing at 55°C, and dramatically increased from 55 to 85°C. ST leachate contents were much higher for ST than for PC, consistent with reports of Kim and Kim (5,7). These results suggest that the cell walls of PC may restrict the leakage of ST molecules leached from swollen and/or gelatinized ST inside intact PC.

Swelling powers of ST and PC isolated from Atlantic and Superior potatoes are shown in Fig. 3C. PC exhibited higher swelling power than ST in a temperature range of 25-55°C, perhaps related to the role of polymeric components (proteins, non-starch polysaccharides) in PC rather than to ST granules (5). The polymeric components such as protein and non-starch polysaccharides (cellulose, hemicellulose, and pectin) are known to swell at low temperatures due to their water holding capacities (23). On the other hand, a dramatic increase in the swelling power of ST and PC was observed above 55°C (Fig. 3C). Swelling of PC resulted from ST contained inside the PC because its polymeric components were solubilized at high temperatures. Nevertheless, the PC swelling powers were lower than the respective ST swelling powers, perhaps because PC contained the non-starch polysaccharides (pectin, hemicellulose, and cellulose). Liu *et al.* (23) suggested that non-starch polysaccharides and proteins in potato flour inhibited the interaction between potato starch and water, thus reducing starch granule swelling. Kim and Kim (5,7) suggested that swelling of ST granules was confined to the limited

Table 2. Mean[1)] values for gelatinization properties of starches and parenchyma cells isolated from Atlantic and Superior potatoes

Cultivar	Potato material	Gelatinization temperature (°C)			Gelatinization enthalpy (J/g dried sample)
		Onset	Peak	Conclusion	
Atlantic	Starch	64.2±0.5[b]	67.5±0.0[b]	76.0±0.0[b]	11.0±0.6[a]
	Parenchyma cell	67.0±0.4[a]	69.7±0.2[a]	76.8±0.1[a]	9.2±0.0[b]
Superior	Starch	61.5±0.0[c]	65.0±0.1[c]	71.4±0.0[d]	10.6±0.2[a]
	Parenchyma cell	65.0±0.0[b]	67.9±0.2[b]	74.9±0.4[c]	9.2±0.1[b]

[1)]Mean values of duplicate measurements; Values sharing the same uppercase letters within columns are not significantly different ($p<0.05$).

volume inside PC, thus restricting overall PC swelling. In short, the presence of intact PC walls may have decreased the solubility and swelling of ST inside PC.

Thermal properties The gelatinization properties of ST and PC were investigated using DSC (Table 2). Gelatinization onset, peak, and conclusion temperatures were 64.2, 67.5, and 76.0°C, respectively, for Atlantic ST, and 61.5, 65.0, and 71.4°C, respectively, for Superior ST (Table 2). Gelatinization temperatures were higher for Atlantic ST, perhaps due to a higher amylose content (Table 1). Potato ST with higher amylose contents commonly exhibit higher gelatinization temperatures (24), although the amylose contents of cereal starches (except for high amylose genotypes) were reported to be negatively correlated to gelatinization temperatures (25). The B-type crystals of potato STs were partially involved by their amylose molecules (26). Accordingly, in this study, the higher gelatinization temperature of Atlantic ST may have resulted from retardation of gelatinization of Atlantic ST by amylose molecules.

Gelatinization enthalpy did not significantly ($p>0.05$) differ between Atlantic and Superior ST (Table 2), although the relative crystallinity of Superior ST was significantly ($p<0.05$) higher than for Atlantic ST (Fig. 2). A broader gelatinization temperature range of Atlantic ST may account for these results. The gelatinization temperatures (conclusion temperature-onset temperature) were 11.8 and 9.9°C for Atlantic and Superior ST, respectively (Table 2).

For PC, the gelatinization onset, peak, and conclusion temperatures were 67.0, 69.7, and 76.8°C, respectively, for the Atlantic cultivar, and 65.0, 67.9, and 74.9°C, respectively, for the Superior cultivar (Table 2). Similar to the patterns observed for ST of both potato varieties, the gelatinization temperatures of Atlantic PC were higher than those of Superior PC. However, PC exhibited higher gelatinization temperatures than ST. Kim and Kim (5,7) reported that observed trends can be related to a lack of water available for starch hydration due to the presence of protein, cellulose, hemicellulose, and pectin (in intact PC) that retard hydration and, in turn, retard gelatinization of ST. In contrast, gelatinization enthalpies were lower for PC than for ST (Table 2), although the relative crystallinity of PC was higher than for ST (Fig. 2). An explanation similar to differences in gelatinization temperatures between ST and PC can be advanced for these results. The limited hydration of ST granules caused by the presence of polymeric components in PC restricted the melting of starch crystals, resulting in a reduction in gelatinization enthalpies. Liu *et al.* (27) reported that the gelatinization enthalpy of potato ST was reduced at low moisture levels.

Pasting properties Pasting viscosity profiles of ST and PC isolated from Atlantic and Superior potatoes are shown in Fig. 3D. The solid contents of ST and PC suspensions were 5.4% and 8.0%, respectively, based on RVA testing. This difference in solid contents was related to exceeding the viscosity limitation of the RVA equipment used in this study where the solid content of the Atlantic ST suspension was more than 5.4%. The pasting viscosity of PC was also not developed at a solid content of 5.4% for PC suspensions. Despite differences in the solid contents of ST and PC suspensions, pasting viscosity profiles were valid within a given potato material for the potato cultivar effect.

The pasting viscosities of ST appeared to be much higher at all points of the programmed temperature profile than the values reported herein for PC (Fig. 3D), consistent with the reports of Kim and Kim (5) and of Anantachote (6). It would be further obvious assuming the RVA test at identical solid contents of ST and PC within a given potato cultivar. The observed differences were perhaps related to differences in starch contents between ST and PC. However, the dry starch weights within PC suspensions (2.25 g of PC in 28 g of total suspension weight) were 1.9-2.0 g, in excess of the 1.5 g of dry starch weight within ST suspensions. Thus, observed results may have been related to the repressed swelling of ST granules wrapped around PC walls as mentioned previously. It further supported by much lower swelling powers at 85°C for PC than for ST within a given potato cultivar.

Based on the pasting viscosity profiles of PC, an unexpected increase in pasting viscosity of both PC varieties was observed immediately when the RVA operation progressed for 6-7 min (Fig. 3D). When pastes recovered

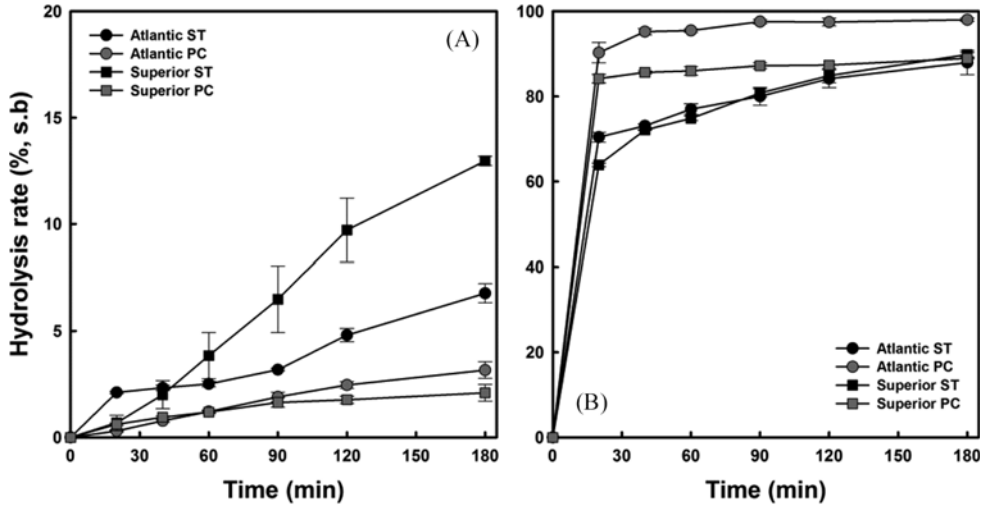

Fig. 4. Hydrolysis pattern of starches (ST) and parenchyma cells (PC) isolated from Atlantic and Superior potatoes in the uncooked (A) and cooked (B) states.

after completion of RVA testing and were viewed under LM using Congo red and iodine staining, the pastes consisted of the intact and damaged PC including starch pastes, the empty PC, and the released starch molecules (images not shown). Based on LM observation, PC containing starch pastes were probably damaged by a constant shear force during the operation time of 6-7 min, resulting in release of starch pastes from the interior of damaged PC (continuous phase in the PC paste). Thus, relative concentrations of the polymeric components, including starch molecules, cellulose, hemicellulose, pectin, and proteins, in the continuous phase of the PC paste were increased, resulting in an overall increase of PC paste viscosities.

***In vitro* starch digestibility** Starch hydrolysis of ST and PC isolated from Atlantic and Superior potatoes was investigated using pancreatic α-amylase in both uncooked and cooked states (Fig. 4). In the uncooked state, ST exhibited low hydrolysis rates during a digestion period of 180 min (Fig. 4A), in agreement with the report of Noda *et al.* (28). Potato ST with B-type crystal packing arrangement exhibited greater resistance against amylolytic enzymes (28). Also, Atlantic ST exhibited lower hydrolysis rates than Superior ST (Fig. 4A), due to higher phosphorous content in Atlantic ST (Table 1). Noda *et al.* (28) noted that the phosphorus contents of potato ST were negatively correlated with digestibility values. However, PC was much less hydrolyzed than respective ST during the digestion period (Fig. 4A). These findings may be resulted from differences in morphological characteristics between ST and PC. The PC prepared in this study entrapped ST granules due to intact cell walls. Accordingly, the lower digestibility of PC may have been due to PC walls acting as a barrier to protect ST granules against attack by amylolytic enzymes. Atlantic PC exhibited a significantly (p<0.05) higher hydrolysis rate than Superior PC during a digestion period of 120-180 min (Fig. 4A), suggesting that the Superior PC wall exhibited a stronger effect as a protective barrier. The PC walls of vegetables are known to contain channel structures of different sizes through which nutrients and enzymes move in both directions (29). Consequently, the smaller size and fewer number of channel structures in the Superior PC wall might result in a lower hydrolysis rate.

In the cooked state, the rapidly digestible fraction (digested within 20 min) (18) was increased in the order of Atlantic PC>Superior PC>Atlantic ST>Superior ST (Fig. 4B). After 20 min of digestion, the hydrolysis rates of all ST and PC varieties gradually increased or reached a plateau, and maximum hydrolysis rates were achieved at 180 min of digestion (Fig. 4B). The hydrolysis rates of Atlantic and Superior ST did not significantly (p>0.05) differ during the digestion period of 30-180 min. Hydrolysis trends were opposite to trends observed for the uncooked state. ST pastes gelatinized in a boiling water bath may have formed partial gel structures via amylose-amylose interactions during cooling to 37°C, thus retarding starch hydrolysis by amylolytic enzymes. However, partially and/or completely gelatinized ST might remain predominantly inside swollen PC, although some gelatinized ST was released. Swollen PC might retard or inhibit amylose-amylose interactions, as supported by a reduction in starch leachate contents of PC relative to ST (Fig. 3B). Also, the channel structures of the PC walls might become broader due to swelling of PC, facilitating infiltration of amylolytic enzymes into swollen PC. Consequently, the released starch molecules and the partial and/or completely gelatinized starches within swollen

PC could be easily hydrolyzed by amylolytic enzymes.

In conclusion, dehydrated potato PC exhibited lower starch leaching and swelling powers, higher gelatinization temperatures, and lower pasting viscosities. The physical properties of PC were different from those of potato ST, probably due to morphological characteristics that different numbers of ST granules agglomerated in the limited cell volume of PC to form huge granules. Thus, dehydrated potato PC is a potential potato material for replacement of existing potato starch and flour. This study illustrated the modification in morphology of potato materials and resulting changes in physical properties. For the purpose of moderation of sugar intake, dehydrated potato PC can be considered as either a main or minor ingredient in a low-moisture food system. Further study for high-moisture food systems is needed for development of methods to reinforce the outer walls of individually separated PC.

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