Carbohydrate Polymers 117 (2015) 845–852

Contents lists available at ScienceDirect

Carbohydrate Polymers

journal homepage: www.elsevier.com/locate/carbpol

Physicochemical properties of dehydrated potato parenchyma cells with ungelatinized and gelatinized starches

Eun-Jung Kim, Hyun-Seok Kim *

Department of Food Science and Biotechnology, Andong National University, 1375 Gyeongdong-ro, Andong-si, Gyeongsangbuk-do 760-749, Republic of Korea

ARTICLE INFO

Article history:
Received 5 February 2014
Received in revised form 8 October 2014
Accepted 13 October 2014
Available online 24 October 2014

Keywords:
Potato
Potato parenchyma cells
Pectinase
Physicochemical property

ABSTRACT

Potato parenchyma cells were characterized to identify the function of intact parenchyma cell walls on their physicochemical properties. Parenchyma cells were separated using pectinase from raw and cooked potatoes (R-Cell and G-Cell, respectively), and investigated with respect to their morphology, chemical composition, starch leaching and swelling power, gelatinization, and pasting property. Potato flour (RPF) and potato granule (PGL) prepared in laboratory were used as controls of R-Cell and G-Cell, respectively. Protein and ash were lost during parenchyma cell isolation. Ungelatinized and gelatinized starches within parenchyma cells were tightly wrapped by intact parenchyma cell walls. Compared to their controls, the parenchyma cell walls prevented starch leaching from R-Cell and G-Cell. R-Cell exhibited the reduced swelling powers and pasting viscosities, while the opposite patterns were observed for G-Cell. R-Cell revealed the increased gelatinization temperatures than native potato starch. Overall, potato parenchyma cells may expand the industrial availability of dehydrated potato products.

1. Introduction

Potato (*Solanum tuberosum* L.) is one of the most important crops as carbohydrate sources in human diets and as industrial commodities for the potato-based foods and the starch production (Šimková, Lachman, Hamouz, & Vokál, 2013). Potato has been cultivated predominantly in North America, EU, and Asia with a worldwide annual production of 374.4 million tons in 2011 (Ek, Brand-Miller, & Copeland, 2012; NPC, 2013). Relative to other crops containing cereals, potato possesses relatively higher amount of starch (about 75% of potato dry matter), and better quality of protein (2.8–14.6% of potato dry matter) with considerable essential amino acids (e.g., lysine, methionine, tryptophan) (Burlingame, Mouillé, & Charrondière, 2009; Kwon et al., 2008). Also, it is abundant in micronutrients such as vitamins (C and B-complex), minerals (potassium, magnesium, calcium, phosphorus, and iron), colorants (carotenoids and anthocyanins), and antioxidant phenols (Burlingame et al., 2009). Due to its rich nutrients, thus, potato as a staple food has been consumed widely in the Western world and is increasingly becoming a staple in developing countries (Ek et al., 2012).

The fresh and processed potatoes, apart from starch production, are generally utilized in North America and EU. Per capita consumption of the processed potatoes subjected to the varied treatments (e.g., freezing, frying for potato chips and shoestrings, dehydrating, canning) was estimated to be about 2.1 times higher than that of the fresh counterparts in USA in 2010 (NPC, 2013). Though dehydration is underutilized among the noted potato processing, the dehydrated potato products (potato flakes and granules) appear to possess great potential for increasing market share of the processed potato products, due to their availability, convenience, low cost, versatility, and stability as a potential food ingredient (Anantachote, 2009). Also, their possible merit may be to resolve the difficulties in storage of the fresh potatoes and the gradual decline in their end-use qualities during storage (Kaur, Singh, Ezekiel, & Sodhi, 2009). To prepare the dehydrated potato products, meanwhile, the fresh potatoes first undergoes heat treatment (e.g., blanching, steaming, boiling), which partially and/or completely gelatinize potato starches within potato tissues. As a result, the dehydrated potato products are easily digested by amylolytic enzymes, belonging to high GI (glycemic index) food category (Camire, Kubow, & Donnelly, 2009; Ek et al., 2012). There is a drift toward avoiding high GI foods for persons who suffer from metabolic diseases (e.g., obesity, type-2 diabetes, cardiovascular disease) and want to maintain or reduce body weight (Higgins, 2004). Though potatoes contain abundant nutrients as a staple food, the consumption of the fresh and processed potatoes mainly

* Corresponding author. Tel.: +82 54 820 5846; fax: +82 54 820 6264.
E-mail address: khstone@andong.ac.kr (H.-S. Kim).

http://dx.doi.org/10.1016/j.carbpol.2014.10.038
0144-8617/

in the developed countries may tend to be reduced due to their high glycemic responses (Camire et al., 2009). Thus, the dehydrated potato products to moderate their glycemic response would be developed to further expand utilization of the dehydrated potato-based products.

A recent attempt was to develop the dehydrated potato product that did not involve starch gelatinization resulted from heat treatment for preparing the conventional dehydrated potato products (Anantachote, 2009). designed the isolation methods of individual parenchyma cells from potato whole-tissues using pectinase and the alkaline solution of NaOH and chelating agent, and successfully prepared the dehydrated potato parenchyma cells containing ungelatinized starches. The morphology and physicochemical property of the resultant potato products were compared depending on potato varieties and isolation methods. Nevertheless, Anantachote (2009) did not verify functions of intact parenchyma cell walls on the characteristics of potato parenchyma cells with ungelatinized starches.

Thus, the objective of this study was to prepare and characterize individual parenchyma cells with ungelatinized and gelatinized starches from potato whole-tissue using pectinase, and to identify the effects of intact parenchyma cell walls on their physicochemical properties so as to validate availability of the dehydrated potato parenchyma cells in an aspect of their processing applications.

2. Materials and methods

2.1. Materials

A potato cultivar, Dubaek, was the source of potato materials prepared in this study. Potato (cultivated in June, 2013 and stored for 2 weeks at 4 °C) was obtained from Dr. Se-Jin Hong of the Department of Horticulture at Gangneung-Wonju National Univeristy (Gangneung, Korea). Pectinase (endo-polygalacturonase from *Aspergillus niger*, activity >1 U/mg) and pancreatin from porcine pancreas (P-7545, 8× USP/g) were purchased from Sigma-Aldrich Co. (St. Louis, MO, USA). Amyloglucosidase (3300 U/ml), total starch assay kit (K-TSTA), and glucose oxidase–peroxidase assay kit (GOPOD; K-GLUC) were obtained from Megazyme International Ltd. (Wicklow, Ireland). All chemicals and reagents used in this study were of analytical grade.

2.2. Preparation of native potato starch (NPS)

NPS was prepared according to the method of Liu, Weber, Currie, and Yada (2003) with slight modification. Washed, peeled potatoes (1 kg) were sliced to 1 cm thickness, and immersed for 30 min in 0.1% (w/v) sodium bisulfite (1000 ml). The slices were ground at high speed for 2 min using a mixer (HMF-3450S, Hanil Electric, Seoul, Korea), and pass through 140-mesh sieve to recover starch milk from potato pulp. The collected starch milk was held at 4 °C for 4 h to precipitate starch granules, after which the supernatant was carefully discarded and the starch cake was re-suspended in deionized water (DIW; 1 l). The noted procedure (re-suspension, precipitation, and starch cake recovery) was repeated a total of 4 times. The final starch cake was suspended in absolute ethanol (500 ml), stirred for 30 min, recovered on a Büchnel funnel, and air-dried.

2.3. Preparation of potato parenchyma cells (R-Cell) with ungelatinized (granular) starches

R-Cell was isolated from raw potato whole-tissues according to an enzymatic isolation method of Anantachote (2009) with slight modification. The reaction medium was prepared by pre-incubation of pectinase (0.5 U/ml) in 0.1 M citrate buffer (pH 3.5, 350 ml) at 50 °C for 30 min. Washed, peeled potato was cut in a cube form (1 cm × 1 cm × 1 cm), and rapidly washed in cold water to remove starch granules exposed on the surface of potato cubes. Potato cubes (100 g) and ascorbic acid (140 mg) were put into the reaction medium, followed by incubation at 50 °C for 3 h under continued stirring (100 rpm) with an overhead stirrer (MS-3060, Misung Scientific Co. Ltd., Yangju, Korea). After 3 h, the potato tissue suspension was passed through a series of sieves (20 and 140 mesh). While potato materials on a 20-mesh sieve (potato tissue residues) were discarded, those on a 140-mesh sieve (R-Cell) were washed with excess DIW on the sieve to remove free starch granules and pectin/parenchyma cell wall hydrolysates. The resultant R-Cell was washed with absolute ethanol, recovered on a Büchnel funnel, and air-dried. For preparation of potato flour (RPF; a control of R-Cell), also, the washed, peeled, and sliced potatoes (1 kg) were soaked for 24 h in cold absolute ethanol (1 l), after which the potato slices were dried at 50 °C for 48 h, ground, and passed through a 50-mesh sieve.

2.4. Preparation of potato parenchyma cells (G-Cell) with gelatinized (non-granular) starches

For G-Cell preparation, potatoes were first treated according to the method of Ooraikul (1974) with modification. The washed, peeled potatoes were steamed for 30 min, and cooled at 25 °C until the temperature of the cooked potatoes was lowered to 70 °C. Then, the cooked potatoes were mashed with a conventional potato masher, and frozen at −25 °C for 48 h. The frozen potato mash (200 g) was thawed at 25 °C for 3 h, mixed with 0.1 M citrate buffer (pH 3.5; 350 ml), and pre-incubated for about 15 min until the mashed potato suspension was reached to 50 °C. Then, ascorbic acid (140 mg) and pectinase (0.5 U/ml) were added to the suspension, and the reaction mixture was further incubated at 50 °C for 3 h under continued stirring (100 rpm) (Anantachote, 2009). After 3 h, the resultant G-Cell was post-treated and recovered as depicted in Section 2.3 for R-Cell preparation. Moreover, potato granules (PGL) as a control of G-Cell were prepared according to the procedures (except for the granulation step) for the production of a commercial potato granule. Briefly, the thawed potato mash (previously obtained for G-Cell preparation) was pre-dried at 50 °C until its moisture content was in the range of 35–40%. The resultant potato mash was further dried at 50 °C using a fluid-bed dryer (BD-600, Irea Tech, Daejeon, Korea) for 24 h, and passed through 50-mesh sieve.

2.5. Field-emission scanning electron microscopy (FE-SEM)

Potato materials, except for R-Cell, were dusted onto a double-sided adhesive carbon tape of an aluminum specimen stub. For R-Cell, it (100 mg) was dispersed in DIW (2 ml), and subsequently mixed with absolute ethanol (8 ml). One drop of R-Cell suspension was mounted onto an aluminum stub using a disposable dispenser, followed by drying at 35 °C for 24 h. The specimens was coated with a 20 nm layer of gold:palladium (60:40), and observed using a field-emission scanning electron microscope (JSM-6700F, Jeol Ltd., Tokyo, Japan) at an accelerating potential of 5 kV and 600 times magnification.

2.6. Chemical composition

Moisture, protein (%N × 6.25), lipid, and ash contents of potato materials were analyzed according to AACC Methods 44-19, 46-08, 08-01, and 30-26, respectively (AACC, 2000). Carbohydrate contents were calculated as subtracting the sum (%, d.b.) of protein, lipid, and ash contents from 100. Total starch contents were assayed using a total starch assay kit according to AACC Method

76-13 (AACC, 2000). Apparent amylose contents were determined with the colorimetric method outlined by Morrison and Laignelet (1983). Phosphorus contents were analyzed via inductively coupled plasma–atomic emission spectroscopy (ICP–AEC) (Anderson, 1996).

2.7. Swelling power and starch leaching

Potato material (0.5 g, d.b.) was mixed with DIW (25 ml) in a 50-ml centrifuge tube. The suspension was heated for 30 min (with periodically vortexing) at predetermined temperatures (25, 40, 55, 70, 85, 100 °C), and cooled to ~15 °C for 20 min in a cold water bath. The swollen potato materials were recovered by centrifugation (2000 × *g*, 30 min), and the supernatant were carefully transferred in a 50-ml volumetric flask. The tube was inverted and allowed to drain for 10 min, followed by precisely measuring the tube weight. Swelling power (SP) was calculated as the ratio of weights of the swollen potato material to the initial counterpart. For starch leaching, the supernatant in the volumetric flask was adjusted to 50 ml with dimethyl sulfoxide. Starch contents in the diluted supernatant were determined by the colorimetric method of Chrastil (1987). Starch leaching was calculated as the percent ratio of starch contents (converted into amylose) in the diluted supernatant to total starch contents in the initial potato materials.

2.8. Thermal properties

Gelatinization properties of potato materials were investigated with a differential scanning calorimeter (Q2000, TA Instruments, New Castle, DE, USA) (Kim, Patel, & BeMiller, 2013). The potato material (5 mg, d.b.) was directly weighed in a pan, followed by addition of DIW up to a total weight of 20 mg. The pan was hermetically sealed and equilibrated at room temperature (~24 °C) for 18 h, after which it was scanned from 10 to 100 °C at a heating rate of 5 °C/min. A sealed empty pan was used as a reference, and indium was used for temperature calibration.

2.9. Pasting properties

Pasting properties of potato materials were investigated with a Rapid Visco Analyser (RVA-3D, Newport Scientific, NSW, Australia). Potato materials (1.5 g or 2.5 g, d.b.) were directly weighed into RVA canisters, followed by addition of DIW up to a total of 28 g. Pasting viscosity profiles and characteristics of potato material suspensions were determined according to standard method 1 (STD1) offered by the supplier.

2.10. Statistical analysis

Potato materials each were repeatedly prepared at least three times, and all characteristic measurements were carried out at least once for each replicate of potato material preparation. Experimental data were analyzed with Analysis of Variance (ANOVA), and expressed as mean ± standard deviation. Tukey's test was employed to identify significant differences among mean values ($p < 0.05$). All statistical computations and analyses were conducted using Minitab 16 (Minitab Inc., State College, PA, USA).

3. Results and discussion

3.1. Morphology

Morphological characteristics of potato materials (NPS, RPF, R-Cell, PGL, G-Cell) were viewed using FE-SEM, and shown in Fig. 1. As reported in literature (Liu, Ming, Li, & Zhao, 2012; Liu, Tarn, Lynch, & Skjodt, 2007), NPS exhibited generally round and oval

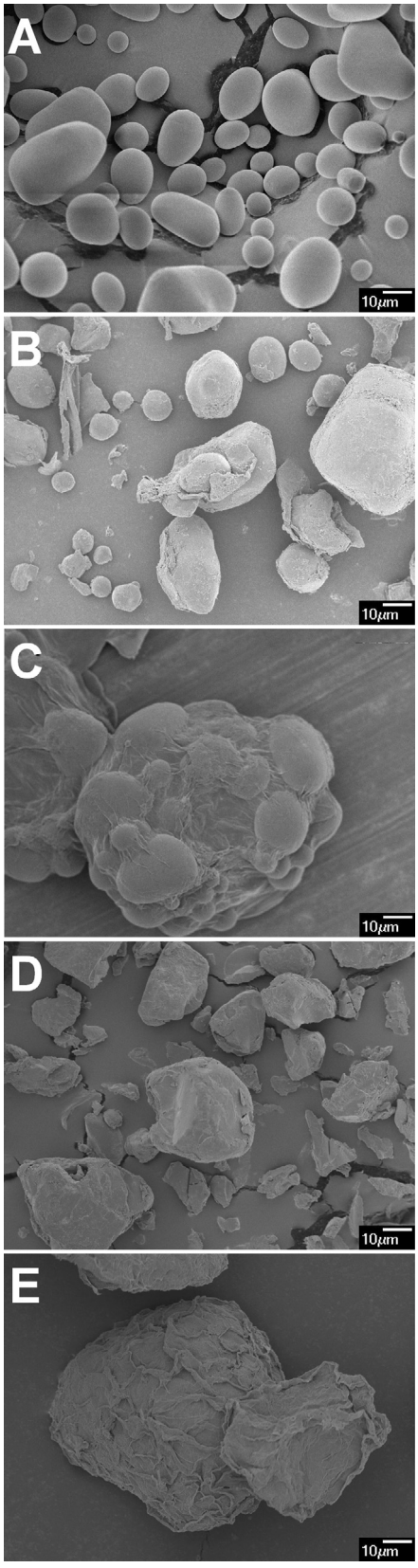

Fig. 1. SEM images of potato materials prepared from Dubaek potato: (A) native potato starch [NPS], (B) potato flour [RPF], (C) potato parenchyma cell with ungelatinized potato granule [G-Cell], (D) potato granule prepared in a lab [PGL], (E) potato parenchyma cell with gelatinized starch [G-Cell] (scale bar = 10 μm).

shapes with the varied granule sizes (10–100 μm), and possessed smooth surface structures (Fig. 1A). In RPF, the predominant constituent was free starch granules with rough surface structures that may result from adsorption of potato chemical compounds (i.e., proteins, non-starch polysaccharides, free sugars, organic acid, and so on) to starch granules during drying process. Also, the starch granule clusters, the parenchyma cell wall fragments, and the aggregates of starch granules and parenchyma cell wall fragments were frequently observed (Fig. 1B). R-Cell consisted mainly of intact parenchyma cells containing ungelatinized potato starch granules to the varied extents, although the broken and/or empty cells, and free starch granules were occasionally found (Fig. 1C). Moreover, multi-cell aggregates that some individual cells adhered together were frequently present. The cell wall structures of R-Cell revealed the highly shrunken appearance and were tightly wrapped around starch granules. Its noted morphological characteristics were very similar to those prepared by Anantachote (2009). PGL prepared in a laboratory exhibited irregular shapes with the varied sizes (Fig. 1D), although commercial potato granules were of somewhat round shapes. Different from RPF and R-Cell, PGL was impossible to distinguish starch fractions from parenchyma cell walls and their fragments. G-Cell (relative to PGL) possessing gelatinized starches were fairly round and oval in shape (Fig. 1E). While partially and completely gelatinized starch fractions were not differentiated from G-Cell, the highly shriveled parenchyma cell walls could be identified. Nevertheless, starch materials retrograded after gelatinized appeared to be present within G-Cell.

3.2. Chemical composition

The proximate compositions, and the total starch, apparent amylose and phosphorus contents of five types of potato materials prepared from Dubaek potato were shown in Table 1. Protein contents were 0.2–11.9% for potato materials, and increased in the order PGL > RPF > G-Cell > R-Cell > NPS. The decrease in the protein content of RPF (relative to PGL) may be due to immersion of potato whole-tissues in ethanol, resulting in the partial loss of alcohol-soluble protein (i.e., prolamines) within potato (Leszczyński, 1989). R-Cell and G-Cell, compared to their respective controls (RPF and PGL), exhibited lower protein contents, consistent with the results observed by Anantachote (2009). Anantachote (2009) suggested that the partial dissolution of potato protein fractions under mild acidic conditions (pH 3.5; 3 h) for the enzymatic isolation of parenchyma cells from potato whole-tissues resulted in the reduction in protein contents of dehydrated potato parenchyma cells. Lipid contents for potato materials were 0.2–0.4% without statistical differences. Ash contents were 0.1–4.3% for potato materials. In particular, the ash contents of R-Cell and G-Cell were significantly lower than their respective controls (RPF and PGL). These reductions in ash contents may be due to the exposure of potato tissues to mild acidic reaction media during pectinase reaction as suggested by Anantachote (2009). Carbohydrate contents were 83.6–99.3% for potato materials, and increased in order NPS > R-Cell > G-Cell > RPF > PGL. The higher carbohydrate contents of R-Cell and G-Cell relative to their respective controls (RPF and PGL) were the results of their reductions in protein and ash that were not recovered during the parenchyma cell isolation. On the other hand, the total starch, apparent amylose, and phosphorus contents were 67.6–93.5%, and 506.5–702.5 ppm, respectively, for potato materials (Table 1). Total starch and phosphorus contents increased in the order NPS > R-Cell > G-Cell > RPF > PGL, coincident with their respective carbohydrate contents. However, the apparent amylose contents (based on dry starch weights) of potato materials ranged from 23.0 to 25.4%, and did not statistically differ for potato materials (Table 1). The statistically similar apparent amylose contents may suggest that the potato processing methods adopted in this study minimize the loss of amylose molecules from raw and cooked potato whole-tissue during treatment.

3.3. Starch leaching and swelling power

The effects of intact parenchyma cell walls on starch leaching and SP of dehydrated potato parenchyma cells (R-Cell and G-Cell) were investigated depending on temperatures and shown in Fig. 2. Significant starch leaching from potato materials began to be observed above 55 °C, and the starch leachate contents increased with increasing temperatures (Fig. 2A). Aside from NPS (due to difficulty in separation of the clear supernatants from starch pastes above 70 °C), the contents of starch leachate at 70 and 85 °C increased in order RPF > PGL > G-Cell > R-Cell, although the amount of starches leached from R-Cell and G-Cell was reversed at 100 °C. The noted observations were not associated with total starch contents (R-Cell > G-Cell > RPF > PGL) of potato materials (Table 1). Nevertheless, R-Cell and G-Cell revealed lower contents of starch leachates than their respective controls (RPF and PGL) at given temperatures (70, 85, 100 °C) (Fig. 2A). These phenomena may be due to the fact that both R-Cell and G-Cell were enclosed by intact parenchyma cell walls (Fig. 1C and E). The intact parenchyma cell walls appeared to act as barriers restricting the leakage of starch molecules leached from starch materials in R-Cell and G-Cell out of them during heat treatment in the potato material–water system.

While the distinct patterns in SPs at low temperature range (25–55 °C) were not observed for potato materials, the lowest SP was obtained from NPS (Fig. 2B). For the potato materials (NPS, RPF, R-Cell) containing granular starches, nevertheless, the level of SP increased in order RPF > R-Cell > NSP at given temperatures (25, 40, 55 °C). These patterns could be explained by variations in their non-starch polysaccharide (defined as the differences between carbohydrate and total starch contents) and protein contents, due to the limited SP of granular starches at low temperature range (25–55 °C). Non-starch polymeric components (e.g., non-starch polysaccharide, protein) within cereal flours were known to possess abilities to absorb and hold water, contributing to their water holding capacity and swelling power (Kweon, Slade, & Levine, 2011). The non-starch polymeric component contents (sum of non-starch polysaccharide and protein contents) increased in order RPF (19.3%) > R-Cell (8.5%) > NPS (6.0%) (Table 1), coincident with the patterns observed for their SPs (Fig. 2B). Consequently, the discrepancy in SP among NSP, RPF and R-Cell at low temperature range (25–55 °C) may result from their differences in the contents of non-starch polymeric components instead of granular starches. On the contrary, in potato materials (PGL, G-Cell) possessing non-granular, i.e. gelatinized, starches, SP was higher for G-Cell relative to PGL, while the opposite trend was observed in non-starch polymeric component contents. However, the SPs of G-Cell and PGL paralleled their total starch contents (Table 1). Kweon et al. (2011) noted that the damaged starch, the granular form of which was partially ruptured by the mechanical impact, within cereal flours was easily hydrated, attributable to their water holding capacity (generally determined at 25 °C). Different from PGL, moreover, the intact parenchyma cell walls wrapped around non-granular starches of G-Cell, enhancing its granularity (Fig. 1E). Consequently, the SP pattern of G-Cell and PGL may be greatly influenced by differences in the non-granular (gelatinized) starch contents and granularity between both potato materials, although the contribution of non-starch polymeric component contents to their SP was also present.

On the other hand, a dramatic increase in SP of NPS was observed beginning at 55 °C, above which temperature NPS exhibited a much higher SP than other potato materials (Fig. 2B). Undamaged, granular starches were generally known to be mainly responsible for SP of cereal flours (Kweon et al., 2011). Also, Shi and BeMiller (2002) demonstrated that potato starch granule swelling was inhibited by

Table 1
Mean[a] values for chemical compositions of potato materials prepared from Dubaek potato.

Potato material[b]	Proximate compositions (%, d.b.[c])				Total starch (%, d.b.[c])	Apparent amylase (%, s.b.[d])	Phosphorus (ppm)
	Protein	Lipid	Ash	Carbohydrate			
NPS	0.2 ± 0.1^{e}	0.4 ± 0.1^{a}	0.1 ± 0.0^{d}	99.3 ± 0.3^{a}	93.5 ± 0.2^{a}	24.1 ± 0.7^{ab}	702.5 ± 2.1^{a}
RPF	8.9 ± 0.2^{b}	0.3 ± 0.0^{a}	3.7 ± 0.1^{b}	87.3 ± 0.1^{d}	76.9 ± 0.3^{d}	25.2 ± 0.4^{a}	576.5 ± 0.4^{d}
R-Cell	4.6 ± 0.3^{d}	0.3 ± 0.0^{a}	0.5 ± 0.0^{c}	94.3 ± 0.3^{b}	90.4 ± 0.3^{b}	23.6 ± 0.8^{b}	677.7 ± 3.9^{b}
PGL	11.9 ± 0.0^{a}	0.2 ± 0.0^{ab}	4.3 ± 0.1^{a}	83.6 ± 0.1^{e}	67.6 ± 0.4^{e}	23.2 ± 0.6^{b}	506.5 ± 1.9^{e}
G-Cell	6.8 ± 0.1^{c}	0.3 ± 0.0^{a}	0.5 ± 0.1^{c}	91.4 ± 0.1^{c}	86.1 ± 0.5^{c}	23.0 ± 0.8^{b}	645.6 ± 5.2^{c}

[a] Mean values of three replicate measurements; values sharing the same lowercase letters within columns are not significantly different at $p < 0.05$.
[b] NPS, RPF, R-Cell, PGL, and G-Cell were referred to as native potato starch, potato flour, potato parenchyma cells with ungelatinized starch granules, potato granule prepared in a laboratory, and potato parenchyma cells with gelatinized starch, respectively.
[c] Dry weigh basis.
[d] Dry starch weight basis.

the aqueous solutions of anionic hydrocolloids (sodium alginate, carboxymethylcellulose, pectin, xanthan, carrageenans). Accordingly, at high temperature range (55–100 °C), the lower SP of four potato materials (RPF, R-Cell, PGL, G-Cell) relative to NPS, may be due to their less granular starch contents and more pectic substances which were probably present even in R-Cell and G-Cell isolated by pectinase treatment (Anantachote, 2009).

In cases of R-Cell with ungelatinized starch granules, it exhibited generally lower SP than RPF (its control) over applied temperatures. Also, the SP of R-Cell much more gradually progressed at the temperature range of 70–100 °C than that of NPS, though differences in total starch contents between NPS and R-Cell were only 3.1%. Thus, these findings suggested that the intact parenchyma cell walls appeared to retard or inhibit swelling of starch granules in R-Cell, although the impacts of differences in chemical compositions among them may not be completely excluded. Regarding G-Cell and PGL (its control) with gelatinized starches, the gradual increase in SP was observed with increasing temperatures from 25 to 100 °C, and also, the SP was higher over all temperatures for G-Cell than PGL. As previously suggested, the noted observation may be the result of differences in total starch content and granular structure between G-Cell and PGL. Above all, the loss of starch materials at the high temperature range was minimized by intact parenchyma cell walls of G-Cell (relative to PGL) (Fig. 2A), enhancing its SP. Overall results suggested that the intact parenchyma cell walls may restrict both leaching and swelling of ungelatinized and gelatinized starches within dehydrated potato parenchyma cells.

Table 2
Mean[a] values for thermal characteristics of potato materials prepared from Dubaek potato.

Potato material[b]	Gelatinization (or melting) temperature (°C)			Gelatinization (or melting) enthalpy (J/g)
	Onset	Peak	Completion	
NPS	63.5 ± 0.1^{c}	66.8 ± 0.1^{c}	71.9 ± 0.2^{d}	16.3 ± 0.1^{a}
RPF	66.8 ± 0.2^{a}	71.1 ± 0.0^{a}	75.5 ± 0.0^{b}	11.6 ± 0.1^{c}
R-Cell	67.0 ± 0.1^{a}	70.3 ± 0.3^{b}	74.6 ± 0.4^{c}	14.9 ± 0.2^{b}
PGL	50.6 ± 0.1^{d}	61.1 ± 0.1^{d}	69.3 ± 0.2^{e}	5.6 ± 0.5^{d}
G-Cell	64.3 ± 0.2^{b}	70.7 ± 0.4^{b}	77.0 ± 0.5^{a}	1.3 ± 0.0^{e}

[a] Mean values of three replicate measurements; values sharing the same lowercase letters within columns are not significantly different at $p < 0.05$.
[b] NPS, RPF, R-Cell, PGL, and G-Cell were referred to as native potato starch, potato flour, potato parenchyma cells with ungelatinized starch granules, potato granule prepared in a laboratory, and potato parenchyma cells with gelatinized starch, respectively.

3.4. Thermal property

Gelatinization properties of potato materials were investigated with DSC and depicted in Table 2 and Fig. 3. For potato materials (NPS, RPF, and R-Cell) mainly composed of ungelatinized starch

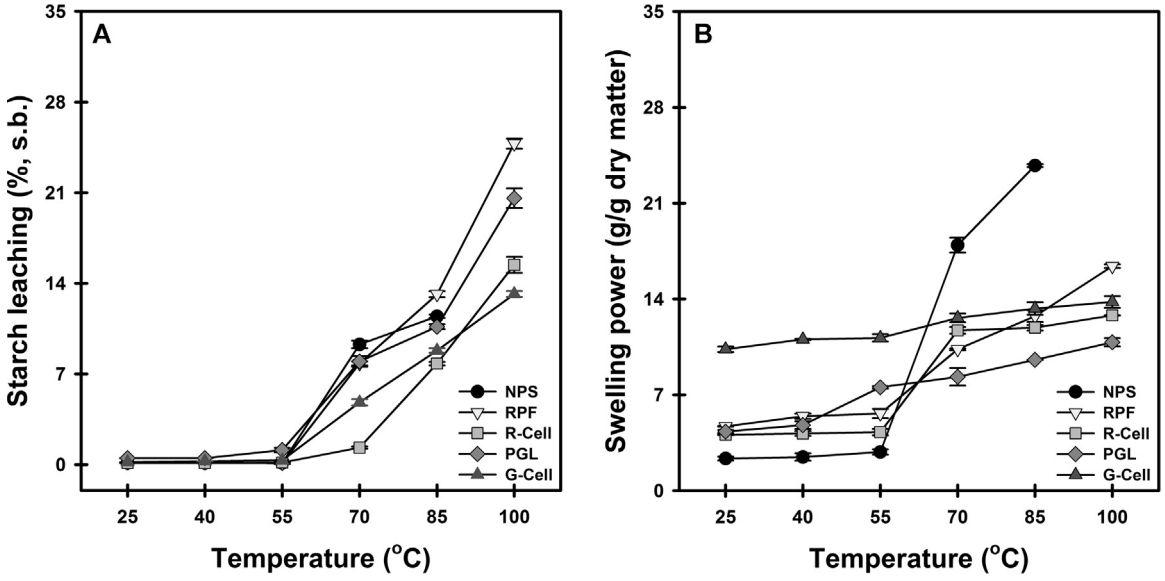

Fig. 2. Starch leaching (A) and swelling powers (B) of potato materials prepared from Dubaek potato (NPS; native potato starch, RPF; potato flour, R-Cell; potato parenchyma cell with ungelatinized potato granule, PGL; potato granule prepared in a lab, G-Cell; potato parenchyma cell with gelatinized starch).

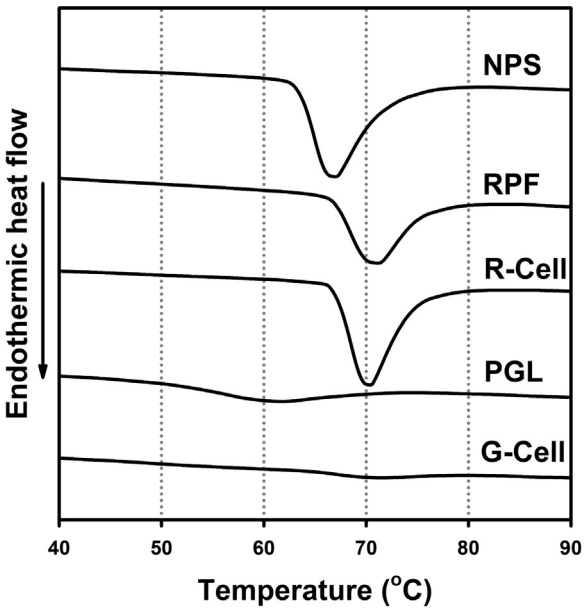

Fig. 3. DSC thermograms of potato materials prepared from Dubaek potato (NPS; native potato starch, RPF; potato flour, R-Cell; potato parenchyma cell with ungelatinized potato granule, PGL; potato granule prepared in a lab, G-Cell; potato parenchyma cell with gelatinized starch).

granules, the gelatinization temperatures of RPF and R-Cell were shifted upward to higher temperatures than those of NPS, consistent with the results of others (Anantachote, 2009; Liu, Yada, & Arul, 2002; Liu Tarn et al., 2007). It may be explained by the partial restriction of water available to starch granule gelatinization in the potato material (RPF and R-Cell)-water system by non-starch polymeric components (protein, non-starch polysaccharide) within RPF and R-Cell, as suggested by Anantachote (2009) and Liu Tarn et al. (2007). Recalling the SP of potato materials (Fig. 2B), RPF and R-Cell exhibited higher SP at low temperature range (25–55 °C) than NPS, suggesting the absorption and holding of water by their non-starch polymeric components prior to those by NPS. Further, their lower SP at high temperature range (55–100 °C) (Fig. 2B) may result from the lack of starch granule hydration by non-starch polymeric components. Based on the noted explanation, accordingly, the limited hydration of granular starches due to the presence of non-starch polymeric components in RPF and R-Cell may retard the breakdown and/or melting of their ordered structures (Liu Yada et al., 2002), resulting in the significant increase in gelatinization temperatures of RPF and R-Cell (relative to NPS). For gelatinization enthalpies, RPF and R-Cell were lower than NPS (Table 2), compatible with the reports of others (Anantachote, 2009; Liu Yada et al., 2002; Liu Tarn et al., 2007). These results were also interpreted by the lack of water available to hydration and in turn, gelatinization of starch granules in RPF and R-Cell due to the existence of their non-starch polymers (Liu Yada et al., 2002). Liu Yada et al. (2002) demonstrated that gelatinization enthalpies of potato dry matter and starch were increasingly reduced with the decrease of moisture contents.

In comparison of gelatinization characteristics of R-Cell to those of RPF, R-Cell possessed higher gelatinization enthalpies than RPF, although gelatinization temperatures were very similar for R-Cell and RPF (Table 2). Also, the gelatinization temperature range (differences between gelatinization onset and completion temperatures) of R-Cell (7.6 °C) became narrower than those of RPF (8.7 °C). This finding paralleled the phenomena generally observed for the annealed starches (Tester, Ansell, Snape, & Yusuph, 2005). Tester et al. (2005) reported the increases in gelatinization temperatures and enthalpies and the decreases in gelatinization temperature ranges of potato starches isolated from potato whole-tissues annealed at 55 °C for 7 days, compared to those of fresh potato whole-tissues. Consequently, starch granules in R-Cell were annealed while potato whole-tissues reacted at 50 °C for 3 h to isolate individual parenchyma cells.

Regarding PGL and G-Cell mainly consisting of gelatinized starches, PGL exhibited lower melting temperatures and enthalpies than NPS, as commonly observed for retrograded starches (Liu Tarn et al., 2007). Also, based on the DSC thermogram and melting characteristics (Fig. 3 and Table 2), PGL possessed a small amount of crystal matters which likely resulted from re-association of starch molecules during freezing and cooling or partial gelatinization of starch granules during steam-cooking. In contrast to PGL, G-Cell exhibited much broader thermogram and lower melting enthalpy (Fig. 3 and Table 2). These results may be due to differences in processing methods. PGL dried as soon as the frozen potato mash was thawed, while G-Cell was subjected to pectinase treatment for 3 h at 50 °C. Accordingly, the thermal properties observed for G-Cell may be due to the breakdown of the ordered structures within the thawed potato tissues by penetration of water molecules into the crystallites. Knorr, Heinz, and Buckow (2006) suggested that while native starch granules is heated in sufficient water, the infiltration of water molecules into starch crystal structures is facilitated, followed by the breakdown of amylopectin clusters and subsequently, unwinding of amylopectin double-helices. On the other hand, the higher melting temperatures of G-Cell (relative to PGL) might be due to the residues of the ordered structures (exhibiting strong crystalline perfection), which could be more resistant to the penetration of water molecules during pectinase treatment. Another possible suggestion might be that the non-starch polymeric components surrounding G-Cell restricted its hydration, retarding its melting.

3.5. Pasting viscosity

Pasting viscosity properties of potato materials were obtained using RVA and shown in Fig. 4. When the concentration of potato materials in their suspensions was 5.4% (1.5 g dry potato material in the total suspension weight of 28 g) for RVA analysis (Fig. 4A), NPS exhibited a typical pasting viscosity profile observed for native potato starches (Liu Tarn et al., 2007). However, the rest potato materials failed commonly to develop pasting viscosities by RVA, although the slight increase in viscosities was observed for RPF. As previously discussed for the SP and gelatinization of potato materials (Sections 3.3 and 3.4), the preferential interaction between potato non-starch polymeric components and water restricted hydration and in turn, swelling of granular and non-granular starches in the potato material–water system, resulting in their less or insufficient pasting viscosities (Liu Tarn et al., 2007). To find the appropriate concentration of potato materials in their suspensions for comparison of pasting properties among potato materials (except for NPS), RVA analysis was conducted as their concentrations increased from 5.4 to 8.9%. Significant pasting viscosities began to be developed at the potato material concentration of 6.3%, and increased with the concentration up to 8.9% (data not shown). The pasting viscosity profiles and characteristics (tested at the potato material concentration of 8.9%) of potato materials (except for NPS) were shown in Fig. 4B and Table 3, respectively. Four potato materials (RPF, R-Cell, PGL, G-Cell) revealed the typical pasting viscosity profiles observed in literature for potato starch and dry matter (Higley, Love, Price, Nelson, & Huber, 2003; Liu Tarn et al., 2007), although the pasting patterns were varied among potato materials (Fig. 4). In comparison of the pasting characteristics of potato parenchyma cells to those of their controls, the peak, trough, and final viscosities of R-Cell were lower than those of RPF (its control), while the opposite trends were observed for breakdown and setback viscosities. As previously discussed in

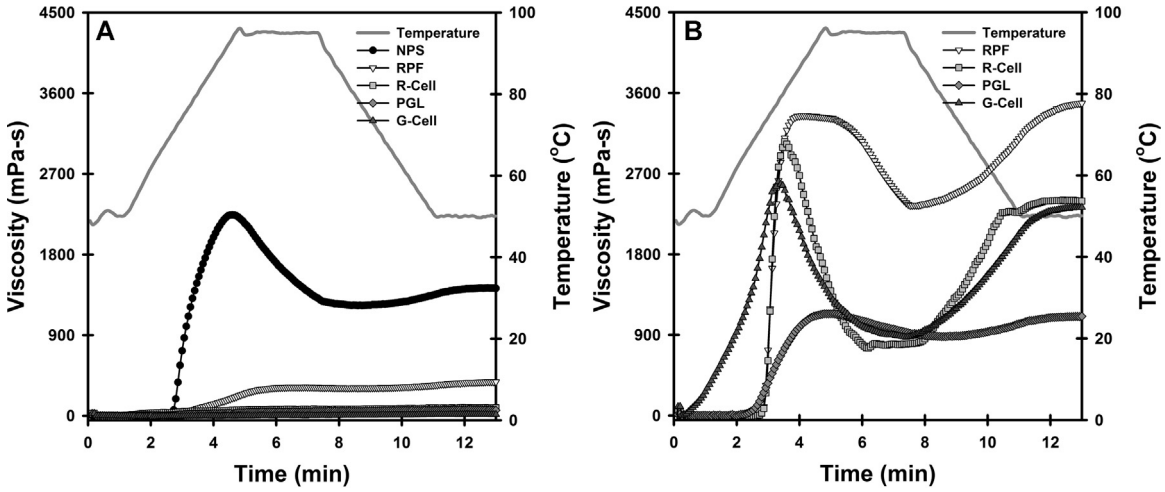

Fig. 4. Pasting viscosity profiles of potato materials prepared from Dubaek potato (NPS; native potato starch, RPF; potato flour, R-Cell; potato parenchyma cell with ungelatinized potato granule, PGL; potato granule prepared in a lab, G-Cell; potato parenchyma cell with gelatinized starch). RVA analyses were conducted independently at potato material concentrations of 5.4% (A) and 8.9% (B).

Table 3
Mean[a] values for pasting characteristics of potato materials prepared from Dubaek potato.

Potato material[b]	Pasting viscosity (mPa s)				
	Peak	Trough	Breakdown	Final	Setback
NPS[c]	2258.5 ± 4.9[d]	1231.0 ± 2.8[b]	1027.5 ± 2.1[c]	1427.0 ± 4.2[d]	196.0 ± 1.4[e]
RPF[d]	3344.5 ± 3.5[a]	2346.0 ± 4.2[a]	998.5 ± 7.8[d]	3482.0 ± 4.2[a]	1136.0 ± 8.5[c]
R-Cell[d]	3053.5 ± 4.9[b]	747.5 ± 7.8[d]	2306.0 ± 2.8[a]	2386.0 ± 8.5[b]	1638.5 ± 0.7[a]
PGL[d]	1132.0 ± 5.7[e]	876.5 ± 6.4[c]	255.5 ± 0.7[e]	1104.0 ± 5.7[e]	227.5 ± 0.7[d]
G-Cell[d]	2605.5 ± 6.4[c]	877.5 ± 3.5[c]	1728.0 ± 9.9[b]	2321.5 ± 3.5[c]	1440.0 ± 7.1[b]

[a] Mean values of three replicate measurements; values sharing the same lowercase letters within columns are not significantly different at $p < 0.05$.
[b] NPS, RPF, R-Cell, PGL, and G-Cell were referred to as native potato starch, potato flour, potato parenchyma cells with ungelatinized starch granules, potato granule prepared in a laboratory, and potato parenchyma cells with gelatinized starch, respectively.
[c] 5.4% potato material concentration (1.5 g dry potato starch in the starch suspension of 28 g).
[d] 8.9% potato material concentration (2.5 g dry potato material in the potato material suspension of 28 g).

Section 3.3, the intact parenchyma cell walls restricted the leaching and swelling of starches in R-Cell, lowering its peak viscosity. Synchronous rupture of swollen parenchyma cells and starch granules may result in a dramatic reduction in trough viscosity of R-Cell. There was generally acceptable relationship that the final viscosities of potato starches and dry matters were positively correlated to their total starch and amylose contents (Liu Tarn et al., 2007; Lu et al., 2011). However, the lower final viscosity of R-Cell (relative to RPF) obtained in this study was not explained by its chemical compositions that R-Cell exhibited the higher total starch and amylose contents than RPF (Table 1). Instead, another possible suggestion might be that the incomplete discharge of viscous starch solution out of the ruptured parenchyma cells likely reduced the interaction among starch molecules in the continuous phase of the R-Cell paste, resulting in the decrease of the final viscosity of R-Cell.

In contrast to the relationship in pasting characteristics between R-Cell and RPF, the pasting characteristics of G-Cell were higher than those of PGL (its control). G-Cell entrapping the gelatinized starches in the intact parenchyma cells may exhibit relatively more stable granularity than PGL, which enhanced its swelling and in turn, viscosity development during pasting. In the case of PGL in which the gelatinized (followed by retrogradation) starches were exposed to the outer environment, however, starch molecules were liberated from PGL prior to arrival at its maximum swelling during pasting, resulting in its lower peak and trough viscosities. Aside from the impacts of parenchyma cell walls on pasting viscosities of G-Cell and PGL, the greater total starch content of G-Cell relative to PGL could explain its higher pasting viscosities, as supported by the common relationship between final viscosity and starch (or amylose) contents of potato starches and dry matters (Liu Tarn et al., 2007; Lu et al., 2011).

4. Conclusions

This study investigated the characteristics of the dehydrated potato parenchyma cells (R-Cell and G-Cell) prepared via pectinase treatment from uncooked and cooked potato whole-tissues. Parenchyma cell walls surrounded the ungelatinized and retrograded potato starches, which appeared to behave like huge granules containing starch granules or retrograded starches. Compared to potato flours that granular and retrograded starch materials were exposed to the outer environment, potato parenchyma cells exhibited different solubility, swelling power, and thermal and pasting properties. Thus, this study demonstrated that a spectrum of the physical property and processing application of potato flours could be expanded through altering their morphologies. Furthermore, the dehydrated potato parenchyma cells could contribute to extending the utilization of the dehydrated potato products in the processed food systems. In the nutritional aspects, however, the use of the dehydrated potato parenchyma cells as main ingredients would consider adding proteins and minerals back to the potato-based food products.

Acknowledgements

This work was supported by a grant from the 'Cooperative Research Program for Agriculture Science & Technology

Development' program (PJ009786), Rural Development Administration, Republic of Korea.

References

AACC. (2000). Approved method of the AACC. In *Methods 08-01, 30-26, 44-19, 46-08, 76-13* (10th ed.). St. Paul, MN: American Association of Cereal Chemists.

Anantachote, A. (2009). *Chemical-assisted separation and characterization of parenchyma cells from potatoes (Solanum tuberosum)*. Moscow, ID: University of Idaho (Unpublished master's thesis).

Anderson, K. A. (1996). Micro-digestion and ICP–AEC analysis for the determination of macro and micro elements in plant tissues. *Atomic Spectroscopy*, *17*, 30–33.

Burlingame, B., Mouillé, B., & Charrondière, R. (2009). Nutrients, bioactive non-nutrients and anti-nutrients in potatoes. *Journal of Food Composition and Analysis*, *22*, 494–502.

Camire, M. E., Kubow, S., & Donnelly, D. J. (2009). Potatoes and human health. *Critical Reviews in Food Science and Nutrition*, *49*, 823–840.

Chrastil, J. (1987). Improved colorimetric determination of amylose in starches or flours. *Carbohydrate Research*, *159*, 154–158.

Ek, K. L., Brand-Miller, J., & Copeland, L. (2012). Glycemic effect of potatoes. *Food Chemistry*, *133*, 1230–1240.

Higgins, J. A. (2004). Resistant starch: Metabolic effects and potential health benefits. *Journal of AOAC International*, *87*, 761–768.

Higley, J. S., Love, S. L., Price, W. J., Nelson, J. E., & Huber, K. C. (2003). The rapid visco analyzer (RVA) as a tool for differentiating potato cultivars on the basis of flour pasting properties. *American Journal of Potato Research*, *80*, 195–206.

Kaur, A., Singh, N., Ezekiel, R., & Sodhi, N. S. (2009). Properties of starches separated from potatoes stored under different conditions. *Food Chemistry*, *114*, 1396–1404.

Kim, H.-S., Patel, B., & BeMiller, J. N. (2013). Effects of amylose–amylopectin ratio on starch-hydrocolloid interactions. *Carbohydrate Polymers*, *98*, 1438–1448.

Knorr, H., Heinz, V., & Buckow, R. (2006). High pressure application for food biopolymers. *Biochimica et Biophysica Acta*, *1764*, 619–631.

Kwon, O.-Y., Kim, M. Y., Son, C. W., Liu, X.-W., Kim, H. C., Yoon, W. K., et al. (2008). Protein and amino acid composition of domestic potato cultivars. *Journal of Korean Society of Food Science and Nutrition*, *37*, 117–123 (in Korean).

Kweon, M., Slade, L., & Levine, H. (2011). Solvent retention capacity (SRC) testing of wheat flour: Principles and value in predicting flour functionality in different wheat-based food processes and in wheat breading—A review. *Cereal Chemistry*, *88*, 537–552.

Leszczyński, W. (1989). Potato tubers as a raw material for processing and nutrition. In G. Lisińska, & W. Leszczyński (Eds.), *Potato science technology* (pp. 11–76). New York, NY: Elsevier Applied Science.

Liu, J., Ming, J., Li, W., & Zhao, G. (2012). Synthesis, characterization and *in vitro* digestibility of carboxymethyl potato starch rapidly prepared with microwave-assistance. *Food Chemistry*, *133*, 1196–1205.

Liu, Q., Tarn, R., Lynch, D., & Skjodt, N. M. (2007). Physicochemical properties of dry matter and starch from potatoes grown in Canada. *Food Chemistry*, *105*, 897–907.

Liu, Q., Weber, E., Currie, V., & Yada, R. (2003). Physicochemical properties of starches during potato growth. *Carbohydrate Polymers*, *51*, 213–221.

Liu, Q., Yada, R., & Arul, J. (2002). Characterization of thermal properties of potato dry matter–water and starch–water systems. *Journal of Food Science*, *67*, 560–566.

Lu, Z.-H., Yada, R. Y., Liu, Q., Bizimungu, B., Murphy, A., Koeyer, D. D., et al. (2011). Correlation of physicochemical and nutritional properties of dry matter and starch in potatoes grown in different locations. *Food Chemistry*, *126*, 1246–1253.

Morrison, W. R., & Laignelet, B. (1983). An improved colorimetric procedure for the determination of amylose in cereal and starches. *Journal of Cereal Science*, *1*, 9–20.

NPC. (2013). *2013 Potato statistical yearbook*. Washington, DC: National Potato Council.

Ooraikul, B. (1974). Production of potato granules. U.S. patent no. 4,007,286. Washington, DC, USA: U.S. Patent and Trademark Office.

Shi, X., & BeMiller, J. N. (2002). Effects of food gums on viscosities of starch suspensions during pasting. *Carbohydrate Polymers*, *50*, 7–18.

Šimková, D., Lachman, J., Hamouz, K., & Vokál, B. (2013). Effect of cultivar, location and year on total starch, amylose, phosphorus content and starch grain size of high starch potato cultivars for food and industrial processing. *Food Chemistry*, *141*, 3872–3880.

Tester, R. F., Ansell, R., Snape, C. E., & Yusuph, M. (2005). Effects of storage temperatures and annealing conditions on the structure and properties of potato (*Solanum tuberosum*) starch. *International Journal of Biological Macromolecules*, *36*, 1–8.