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Physicochemical properties of starches during potato growth

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Abstract

The characterization of physicochemical properties of starch during potato growth is critical to the development of new starch products. Desired functional properties may be achieved by controlling the growth period, without further physical or chemical modification of the starch. In this study, starch was extracted from three potato cultivars (Shepody, Snowden, and Superior) during growth. The physicochemical properties of starches were characterized by different analytical techniques. Gelatinization and retrogradation of starches were measured using differential scanning calorimetry. Starch crystalline structure was evaluated by X-ray diffraction. Rapid viscosity analysis was employed to measure starch paste viscosity and pasting temperature. Starch obtained from potatoes with a shorter growth time had higher gelatinization temperature, pasting temperature, lower peak viscosity (half that of normal starch) and higher final viscosity (double the value of normal starch). Results indicate that physicochemical properties of starches varied among the potato cultivars, as well as growth time. Different starch granular size, phosphorous content and amylose content could be major factors influencing starch functional properties.

Keywords: Immature potatoes; Starch; Thermal behavior; Gelatinization; Retrogradation; Swelling; Rapid viscosity analysis; X-ray diffraction

1. Introduction

Potatoes are grown as a vegetable for consumption, and also as a raw material for processing into products, such as starch, potato chips, and French fries. Of all the commercial starches, potato starch exhibits the highest swelling power and gives the highest viscosity on pasting; it excels in film forming and binding characteristics (Mitch, 1984). The properties of native potato starch, however, may not be desirable for all applications. Many methods, including physical and chemical, are available to modify potato starch to meet specific applications. Starch modification is achieved either by the starch producer, who modifies starch without disrupting the granules, or by the end-user who cooks and modifies the starch in a single step operation (Wurzburg, 1986). Modified starches are used in a wide variety of food and non-food applications. However, due to the federal regulations governing levels of chemical modification and the high cost of physical modification, an alternative approach needs to be explored to alter the starch properties by means other than chemical or physical processes.

Starch properties vary with potato cultivars and growth time (Lisinska & Leszczynski, 1989). The granular size, peak viscosity, and phosphate content increases during potato growth (Christensen & Madsen, 1996). The amylose content of starch remains unchanged (Halsall, Hirst, Jones, & Sansome, 1948); this observation was confirmed by Christensen and Madsen (1996).

Although much research has been carried out on the characterization of physicochemical properties of potato starch, no information is available about swelling power, thermal properties of gelatinization and retrogradation, crystalline structure and molecular characteristics of starch during potato growth. The objectives of this study are to characterize the physicochemical properties of starches from potatoes of different cultivars and growth times; and to achieve desired starch functionality without chemical and physical modification by controlling potato growth time and selecting potato varieties with certain characteristics.

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2. Materials and experimental methods

2.1. Materials

2.1.1. Potatoes

Three potato varieties (Superior, Shepody, and Snowden) grown in Cambridge, Ont. (Canada) were harvested at different growth times in the year 2000 season and were stored at room temperature for 1 day prior to the isolation of dry matter and starch.

2.1.2. Potato dry matter

Potato dry matter was obtained by freeze-drying. Dry matter content was determined from the difference in the weight of potato samples before and after freeze-drying. Potato slabs (ca. 5 g, 4 cm × 2 cm × 1 cm) were prepared from the center of tuber and lyophilized in a Freeze Dryer 8 (Labconco®, Kansas City, MO). Potato dry matter was ground and passed through a 149 μm sieve, and subsequently stored in air-tight plastic bags at room temperature (23 °C) until further use. Moisture content was measured by weighing samples (triplicate) before and after drying at 85 °C and 710–740 mm Hg vacuum for 7 h.

2.1.3. Potato starch

Potato tubers were washed, peeled, sliced into 2–3 cm cubes, and soaked in distilled water containing 20 mM sodium bisulphite and 10 mM citric acid for 2 h. The cubes were then disintegrated using a centrifugal juice extractor. The pulp was suspended in distilled water, and the starch milk was collected. The milk was allowed to sediment for a minimum of 30 min, after which the suspended solids were removed by decantation, and the starch sediment was resuspended in water. The starch granules were recovered by vacuum filtration, and washed a minimum of three times and finally, ambient air-dried. The dried starch was passed through a 125 μm sieve, packed in air-tight plastic bags and stored at room temperature until further use (Liu, 1997).

2.2. Analytical methods

2.2.1. Starch content

Starch content was determined based on potato dry matter, as well as fresh tuber weight. To 100 mg potato dry matter, 100 μl (300 U) α-amylase (from *Bacillus* species, Sigma A-6380, St Louis, MO) solution, and 2.9 ml 45 mM MOPS buffer (pH 7.0) were added. The sample was heated in a boiling water bath for 6 min with constant stirring, and was then cooled below 50 °C. 100 μl (20 U) amyloglucosidase (from Rhizopus mold, Sigma A-7255, St Louis, MO) solution and 3.9 ml 200 mM sodium acetate buffer (pH 4.5) were added to the sample. The sample was mixed and incubated at 50 °C for 30 min with constant stirring. The sample was then diluted by adding 10 ml distilled water, mixed thoroughly and centrifuged at 9600*g* for 10 min. The glucose content of supernatants was measured by YSI 2700 Select Biochemistry Analyzer (Yellow Springs, OH). The principle of the reaction is that when a sample is injected into the sample chamber of YSI 2700, glucose diffuses into the membrane, which contains glucose oxidase. The glucose is immediately oxidized to hydrogen peroxide and D-glucono-δ-lactone. The hydrogen peroxide is detected amperometrically at the platinum electrode surface. The current flow at the electrode is directly proportional to the hydrogen peroxide concentration, and hence to glucose concentration. Pure starch from different potatoes was employed as a standard in every batch experiment to ensure there was no difference in enzyme activity. Starch content of potato dry matter was expressed as a ratio of glucose content of the dry matter to glucose content of pure starch following starch hydrolysis. Blank samples (without enzymes) were also measured with the same procedure. Finally, starch content in potato tubers was expressed by multiplying dry matter content by starch content in dry matter. The reported values are means of triplicate measurements.

2.2.2. Granular size of starch

A 'Leica DMRBE' microscope (Leica Microsystem, Inc., Buffalo, NY) equipped with a Sony 3 chip color camera (3 CCD Iris) (model DXC-930) was used to determine size and size distribution of starch granules. Granular starch was dispersed in water (1.25% starch content, w/w) by stirring, and the starch dispersion was placed on a microscopic slide and stained with 0.1N iodine for examination. The images were recorded using Adobe Photoshop 5.0. Images were captured at the same magnification (50 ×) for all starch samples. The size and size distribution of granules were determined using Optimas 6.1 (Optimas Corp., Silver Spring, MD). The images were calibrated using images of calibration micrometer. The long (major) axis of about 40 granules was measured, and average length of granules was calculated.

2.2.3. Total phosphorous content of starch granules

Total phosphorous content of starch granules was measured according to the method of Thomas, Sheard, and Moyer (1967). The reported values are the means of duplicate measurements.

2.2.4. Amylose content of starch

Apparent amylose contents were determined by iodine colorimetry using a modified Williams, Kuzina, and Hlynka (1970) method. Starch and pure amylose and amylopectin solutions were stirred for 10 min in a boiling water bath. The absorbance was measured at 625 nm by a Cary 3C spectrophotometer (Varian Analytical Instrument, Sugar Land, TX).

2.2.5. Swelling factor

Swelling factor of starch from potato harvested at different growth times was determined by the method of

Tester and Morrison (1990). The experimental temperature ranged from 60 to 75 °C.

2.2.6. Wide angle X-ray diffraction

A sealed tube X-ray diffraction instrument (Siemens/Bruker, Madison, WI) with copper radiation ($K_\alpha = 1.5418$ Å), nickel filtered was used. The instrument consisted of a Kristalloflex 760 generator, 3-circle goniometer and Hi-Star area detector, equipped with GADDS software. Operation power was 40 kV and 40 mA. Collimator diameter was 0.8 mm. Sample to detector distance was 10 cm. The center of the detector was positioned at an angle of 25° from incident beam. The samples were prepared in thin-walled (0.01 mm) glass capillary tubes (1.0 and 1.5 mm in diameter for starch and dry matter, respectively). The results were given as X-ray diffraction spectra. The pattern was compared to the characteristic peak of B-type X-ray diffraction (Zobel, 1964).

2.2.7. Differential scanning calorimetry

Thermal analyses were performed using a differential scanning calorimeter (2920 modulated differential scanning calorimetry (DSC); TA Instruments, New Castle, DE) equipped with a refrigerated cooling system (RCS) for starch gelatinization and retrogradation. Samples of potato starch were weighed into high-volume pans (Part number: 900825-902; TA Instruments, New Castle, DE). Distilled water was added using a micropipette to make suspensions with 70% moisture content. Pans were sealed and equilibrated for 2–4 h at room temperature before heating in the DSC. The measurements were carried out at a heating rate of 10 °C/min from 5 to 180 °C. Sample weights were about 20 mg. The instrument was calibrated using indium and an empty pan as reference. The enthalpy (ΔH) of phase transitions was measured from the endotherm and exotherm of DSC thermograms using software (Universal Analysis, Version 2.6D, TA Instruments) based on the mass of dry solid. Onset (T_o) and peak temperature (T_p) of endotherms were also measured from DSC thermograms.

Retrogradation: After heating to 180 °C, samples were cooled to 5 °C. Once the temperature reached 5 °C, the sample was immediately removed from the DSC and stored at 5 °C. After 14 days, the sample pan was removed and placed into the sample holder of the DSC. Stored samples were heated from 5 to 180 °C at 10 °C/min. The enthalpy (ΔH), onset temperature (T_o) and peak temperature (T_p) of the endotherm were measured from DSC thermograms based on dry solid mass. The reported values are the means of duplicate measurements.

2.2.8. Rapid viscosity analysis

A Rapid Visco™ Analyser RVA-4 (Newport Scientific Pty. Ltd, Warriewood, NSW, Australia) was employed to measure the pasting properties of starches (8% dsb, 28 g total weight). Experiments were performed using AACC method 76-21 (AACC, 2000), in which the sample is equilibrated at 50 °C for 1 min, heated at 6 °C/min to 95 °C, held at 95 °C for 5 min, cooled at 6 °C/min to 50 °C, and held at 50 °C for 2 min. The speed was 960 rpm for the first 10 s, then 160 rpm for the remainder of the experiment. Peak viscosity, final viscosity, and pasting temperature of starches were compared from pasting curves. The reported values are the means of duplicate measurements.

2.2.9. Statistical analysis

The statistical analysis was performed using single factor ANOVA for all data. Significant difference was evaluated based on $p \leq 0.05$.

3. Results and discussion

3.1. Starch content of potato tubers during growth

Due to the differences among cultivars in tuber growth rates, the harvest dates were different for the selected cultivars. Superior was planted earlier than Shepody and Snowden seed potatoes. Table 1 presents the dry matter contents of potato tuber and starch content of potato dry matter at different growth times. At the earliest harvest time, dry matter content was 16.6, 21.0, and 18.6% (w/w) in the fresh potato tubers for Superior, Shepody, and Snowden cultivars, respectively. As growth time increased, dry matter content in the tubers increased to its highest level between 64 and 71 days, then decreased. This finding is consistent with a previous study (Kolbe & Stephan-Beckmann, 1997) on dry matter content as a function of tuber growth time. The highest dry matter content was 19.2% for Superior tubers at 64 days, 24.2% for Shepody tubers at 71 days, and 24.0% for Snowden potato at 71 days. Superior tubers had a lower dry matter content than Shepody and Snowden tubers at all harvest days. Starch content of dry matter also varied with potato cultivars and growth or harvest time. In the selected potato dry matters, the starch content ranged between 66 and 80%. Starch content was 66.0, 67.2, and 71.1% in the dry matter of Superior, Shepody, and Snowden cultivars, respectively, harvested at the earliest time. It was 79.7, 74.3, and 75.6% in the dry matter of potato from Superior, Shepody, and Snowden cultivars, respectively, harvested at the longest growth time. Starch content of dry matter was the lowest at the first harvest, then increased to its highest level, followed by a slight decrease. The highest starch content in potato dry matter was 80.4% for Superior potato at 84 days, 78.1% for Shepody potato at 91 days, and 78.4% for Snowden at 91 days.

Starch content was similar for both Shepody and Snowden potato tubers, and was higher than Superior tubers at similar growth times. Starch content increased rapidly over the first 2 months of growth, then decreased slightly as growth progressed. The highest starch content in fresh tuber was 14.9, 18.8, and 18.5% for Superior (64 days), Shepody (71 days), and Snowden (71 days) potatoes, respectively. At

Table 1
Dry matter content of fresh potato tuber and starch content of potato dry matter at different potato growth times

Cultivar	Growth time (day)	Dry matter content in tuber (%, w/w)[a]	Starch content in dry matter (%, w/w)[a]	Starch content in fresh tuber (%, w/w)
Superior	48	16.6 ± 0.2	66.0 ± 1.2	11.0
	56	16.2 ± 0.4	72.7 ± 0.7	11.8
	64	19.2 ± 1.0	77.5 ± 1.0	14.9
	84	17.3 ± 1.0	80.4 ± 0.4	13.9
	117	16.9 ± 1.1	79.7 ± 0.9	13.5
Shepody	55	21.0 ± 0.6	67.2 ± 1.4	14.1
	71	24.2 ± 0.9	77.6 ± 1.3	18.8
	91	20.1 ± 0.9	78.1 ± 1.4	15.7
	112	18.8 ± 1.0	74.8 ± 1.7	14.1
	124	19.8 ± 0.4	74.3 ± 5.2	14.7
Snowden	55	18.6 ± 1.6	71.1 ± 1.2	13.2
	71	24.0 ± 1.3	77.2 ± 3.0	18.5
	91	20.9 ± 0.6	78.4 ± 2.4	16.4
	112	17.8 ± 1.5	75.8 ± 2.8	13.5
	124	19.8 ± 1.0	75.6 ± 1.4	15.0

[a] Value denotes mean ± standard deviation.

these growth times, potato tubers also had the highest dry matter content. However, the starch content was 13.5% in Superior potato, 14.7% in Shepody potato, and 15.0% in Snowden potato at the normal harvest time.

Dry matter and starch content play very important roles in the quality of potato products (Lisinska & Leszczynski, 1989; Pavlista, 1997). Potatoes with higher dry matter or starch content are well suited for food use, processing or starch manufacture (Mitch, 1984). In this study, Shepody and Snowden potatoes had higher starch contents than Superior. The highest starch content in the fresh tuber was found when growth time was about 2 months, although the growth time for producing the highest starch content slightly varied with cultivars in this study. Thus, potatoes with higher dry matter and starch content could be obtained by selecting specific potato cultivars and harvesting at specific times.

3.2. Granular size of starch during potato growth

Granular size (major axis) varied with starch isolated from potato with different cultivars and growth times. However, the shapes of the granules were similar. At the earliest harvest time, average granular size was 19.1, 16.8, and 21.1 μm (Table 2) in the starch isolated from Superior, Shepody, and Snowden cultivars, respectively. As growth time increased, average granular size of starch increased to its highest level, then decreased. At the final harvest time, average granular size was 26.7, 21.5, and 26.8 μm in the potato starch from Superior, Shepody, and Snowden cultivars, respectively. Starch granules from Shepody potato had a smaller size than that of Superior and Snowden potatoes.

3.3. Total phosphorous content of starch during potato growth

Phosphorous content of starch granules varied with potato cultivar and growth time. Total phosphorous content was between 0.038 and 0.069% (Table 2) for starch granules isolated from different potato cultivars and different growth times. At the earliest harvest time, phosphorous content was 0.041, 0.060, and 0.057% in the starch from Superior, Shepody, and Snowden potato cultivars, respectively. As growth time increased, phosphorous content of the starch granules increased to its highest level. During potato growth, the phosphorous content of starch granules was significantly different ($p < 0.05$) for all three cultivars. This finding is consistent with a previous report from Christensen and Madsen (1996). Starch granules from Superior potato had a lower phosphorous content than that from Shepody and Snowden potatoes. Shepody potato starch had the highest phosphorous content of all three cultivars.

3.4. Apparent amylose content of starch during potato growth

Table 3 reports the apparent amylose content of potato starches by iodine colorimetry. For all three cultivars, amylose content was the highest for potatoes harvested at the shortest growth time. Amylose content was 31.4, 33.1, and 31.4% (w/w) in the starch granules from Superior, Shepody, and Snowden cultivars, respectively. Amylose content decreased after the first harvest and remained unchanged during growth of tubers. Amylose content was between 28.3 and 29.5% for Superior starch, between 29.0 and 29.7% for Shepody starch, and between 29.7 and 31.1% for Snowden starch. During potato growth, the amylose content was not significantly different ($p > 0.05$) for Superior and Snowden cultivars, but there was a significant

Table 2
Granular size and total phosphorous content of starch during potato growth

Starch from potato cultivar	Growth time (day)	Granular size (long axis) (μm)	Phosphorous content in starch granule ($\times 10^{-2}$%, w/w)
Superior	48	19.1 ± 7.3	4.1 ± 0.1
	56	26.6 ± 12.0	4.0 ± 0.0
	64	21.4 ± 11.9	3.8 ± 0.0
	84	32.2 ± 15.3	5.2 ± 0.0
	117	26.7 ± 10.4	5.0 ± 0.1
Shepody	55	16.8 ± 10.0	6.0 ± 0.1
	71	16.9 ± 8.4	5.3 ± 0.1
	91	18.0 ± 10.1	6.4 ± 0.1
	112	22.7 ± 11.8	6.4 ± 0.1
	124	21.5 ± 9.0	6.9 ± 0.0
Snowden	55	21.1 ± 9.3	5.7 ± 0.1
	71	18.3 ± 8.2	5.7 ± 0.1
	91	29.6 ± 16.3	5.8 ± 0.0
	112	33.3 ± 15.6	5.8 ± 0.1
	124	26.8 ± 12.6	6.1 ± 0.1

Total phosphorous content in starch: $p = 1.73 \times 10^{-5}$ for all Superior starch, $p = 0.014$ for all Snowden starch, and $p = 5.18 \times 10^{-5}$ for all Shepody starch.

difference for Shepody. No significant difference in amylose content of starch granules was observed for Shepody potatoes after 71 days. This finding is different from previous studies (Christensen & Madsen, 1996; Halsall, Hirst, Jones & Sansome, 1948) which showed no change in amylose content of starch during potato growth.

3.5. Swelling factor of starch at different growth times

Fig. 1 shows the swelling factor of starch granules as a function of temperature and growth time for Shepody potato starch. Swelling factor of starch was greatly influenced by growth time and experimental temperature. For the starch isolated from the earliest harvested potato, the swelling factor was the lowest at all temperatures except at 60 °C compared to that of starch isolated from longer harvest potato. The lowest swelling factors were 5.8, 5.6, 9.0, 25.0, and 26.6 at 61.3, 62.5, 65, 70, and 75 °C, respectively. For starch isolated from potatoes with the longest growth time, the swelling factor was 13.0, 18.4, 30.0, 31.2 and 32.9 at 61.3, 62.5, 65, 70, and 75 °C, respectively. Swelling factor slightly increased as potato growth time increased from 61.3 to 65 °C. The largest change in the swelling factor of starch, except for the starch isolated from earliest harvest potato, was observed between 62.5 and 65 °C as shown in Fig. 1. For the potato starch obtained from the earliest harvest, however, the largest increase in swelling factor occurred between 65 and 70 °C. All potato starches except for the earliest harvest showed a similar and higher swelling factor at temperatures above 70 °C. The change in swelling factor above 65 °C may be due to starch gelatinization. Gelatinization temperature was thus considered a characteristic of starch (Liu, Charlet, Yelle & Arul, 2002). When starch is gelatinized at a certain temperature, molecular organization is disrupted within the granule, and starch-water interactions increase, resulting in a substantial increase in the swelling factor. Swelling factor of starch is also influenced by molecular structure including crystalline structure and chemical composition (Tester & Morrison, 1990). Another factor influencing starch swelling at different temperatures could be the leaching of amylose from starch granules. Therefore, further investigation on amylose leaching from starch granules will be conducted. Differences in swelling

Table 3
Apparent amylose content of starch during potato growth

Superior		Shepody		Snowden	
Growth time (day)	Amylose content (%)	Growth time (day)	Amylose content (%)	Growth time (day)	Amylose content (%)
48	31.4 ± 1.6	55	33.1 ± 1.3	55	31.4 ± 0.1
56	28.8 ± 0.9	71	29.3 ± 0.0	71	30.6 ± 0.4
64	28.3 ± 0.7	91	29.0 ± 0.6	91	31.0 ± 0.7
84	29.3 ± 0.2	112	29.7 ± 1.1	112	31.1 ± 0.4
117	29.5 ± 0.6	124	29.4 ± 0.1	124	29.7 ± 0.1

$p = 0.14$ for all Superior starch, $p = 0.33$ for all Snowden starch, $p = 0.02$ for all Shepody starch, and $p = 0.73$ for all Shepody starch excluding the starch with growth time 55 days.

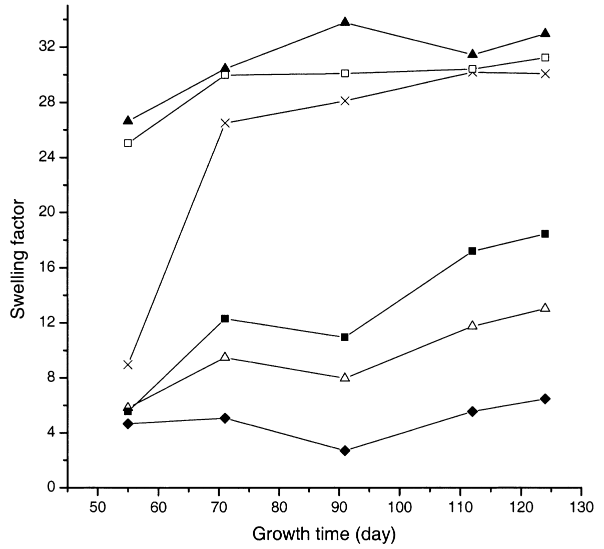

Fig. 1. The swelling factor of starch at 60.0 °C (◆), 61.3 °C (△), 62.5 °C (■), 65.0 °C (×), 70.0 °C (□), 75.0 °C (▲) during Shepody potato growth.

factors indicate that different interactions between amylose and amylopectin may exist in these potato starches.

3.6. X-ray diffraction pattern

Fig. 2 shows the X-ray diffraction pattern of starches extracted from Superior potatoes at different growth times. Starches isolated from Shepody and Snowden potatoes had similar X-ray diffraction patterns as shown in Fig. 2. The characteristic peaks appeared at the Bragg reflection angle 2θ: 5.5, 17.2, and 22.1° for all five starches at different potato growth times. These X-ray diffraction patterns were B-type and the same as commercial potato starch (Zobel, 1964, 1988). The similar X-ray diffraction pattern indicates

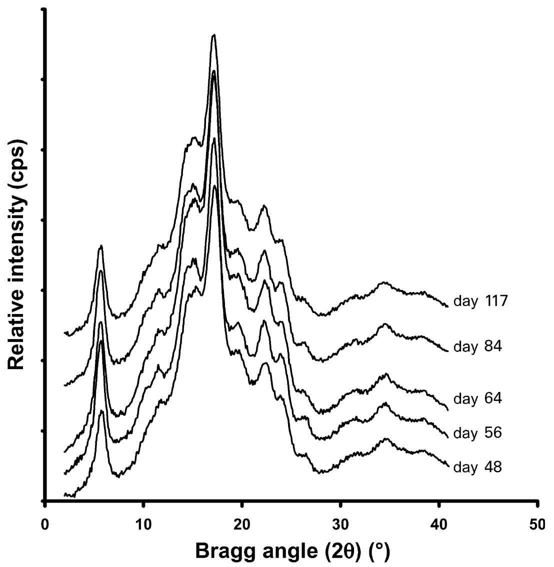

Fig. 2. X-ray diffraction pattern of starches extracted from Superior potato at different growth time. Labeling refers to growth time.

that the organization of semi-crystalline structure of starch was not affected by potato growth time. Although differences existed in the peak intensities among the potato starches examined, more detailed information, such as the crystallinity development during potato growth is to be investigated in the future.

3.7. Gelatinization and retrogradation properties of starches from potato with different growth times

When potato starches were heated in the presence of excess water (70%), a single symmetrical endothermic transition was observed at peak temperatures between 70.0 and 74.8 °C, indicating starch gelatinization (Donovan, 1979). All the starches from different cultivars and growth times had similar thermograms. Table 4 lists the thermal properties of potato starch during potato growth. Onset and peak temperatures of starch gelatinization were the highest at the earliest harvest for the starches isolated from the selected cultivars. The peak temperature was 74.6, 74.8, and 73.3 °C for Superior, Shepody, and Snowden starch, respectively. The higher gelatinization temperature results in the lower swelling factor in starch as seen in the previous discussion. Onset and peak temperatures decreased slightly as potato growth time increased. At the earliest harvest, gelatinization enthalpy was 16.5, 16.5, and 16.9 J/g for Superior, Shepody, and Snowden starch, respectively. It increased slightly as growth time increased. At the final harvest, gelatinization enthalpy was 18.0, 16.8, and 18.0 J/g for Superior, Shepody, and Snowden starch, respectively. No significant difference ($p > 0.05$) in the gelatinization enthalpy, onset temperature and peak temperature ($p > 0.05$) of starch from the same cultivar over the growth period was observed, except for the onset temperature and peak temperature of starch from potatoes with the shortest growth time. We propose that the same X-ray diffraction pattern of starch crystalline structure may contribute to these thermal properties and that no substantial changes occur as tuber growth progresses.

When gelatinized starch was reheated after being stored at 5 °C for 2 weeks, a broader endothermic transition was observed at peak temperatures between 64.7 and 70.2 °C, indicating starch retrogradation had occurred. The peak temperature of retrogradation was the highest for gelatinized starch from potato at the earliest harvest time. It was 66.6, 69.2, and 68.2 °C for Superior, Shepody, and Snowden starch, respectively. The retrogradation enthalpy was 9.5, 8.7, and 8.9 J/g for Superior, Shepody, and Snowden starch, respectively. No significant difference ($p > 0.05$) in retrogradation onset temperatures, peak temperatures and enthalpies was observed among the same cultivar potato starches with different growth times except the earliest harvested potato starch. We suggest that this may be due to the formation of a similar crystalline structure after 2 weeks storage at this temperature. The higher gelatinization temperature in the raw starch results in higher peak

Table 4
Thermal properties of starch during potato growth

Cultivar	Growth time (day)	Gelatinization			Retrogradation		
		ΔH (J/g)	T_o (°C)	T_p (°C)	ΔH (J/g)	T_o (°C)	T_p (°C)
Superior	48	16.5 ± 0.3	68.1 ± 0.3	74.6 ± 0.6	9.5 ± 0.8	46.4 ± 0.1	66.6 ± 0.3
	56	17.1 ± 0.6	66.9 ± 0.1	73.1 ± 0.3	10.0 ± 0.6	46.4 ± 0.1	65.8 ± 0.1
	64	17.2 ± 1.4	65.6 ± 0.2	71.4 ± 0.3	10.1 ± 1.0	46.6 ± 0.1	65.2 ± 0.1
	84	17.0 ± 0.2	65.6 ± 0.1	71.2 ± 0.1	9.5 ± 0.8	46.7 ± 0.0	66.2 ± 0.5
	117	18.0 ± 0.5	65.8 ± 0.1	71.3 ± 0.0	10.0 ± 0.1	48.0 ± 0.8	65.6 ± 0.1
	p-value	0.417[a]	0.000[a]	0.000[a]	0.849[a]	0.028[a]	0.027[a]
			0.002[b]	0.002[b]		0.046[b]	0.086[b]
			0.386[c]	0.383[c]			
Shepody	55	16.5 ± 0.7	67.7 ± 0.1	74.8 ± 0.4	8.7 ± 0.5	N/a[d]	70.2 ± 0.1
	71	16.0 ± 0.3	66.1 ± 0.9	72.0 ± 1.4	7.7 ± 1.1	N/a	67.2 ± 1.2
	91	15.6 ± 0.0	67.9 ± 0.0	74.3 ± 0.0	8.7 ± 0.2	N/a	68.3 ± 0.4
	112	16.1 ± 0.5	66.8 ± 0.5	72.9 ± 0.6	8.4 ± 0.6	N/a	68.5 ± 0.6
	124	16.8 ± 0.3	66.3 ± 0.3	72.1 ± 0.3	8.5 ± 0.3	N/a	68.2 ± 0.2
	p-value	0.168[a]	0.031[a]	0.039[a]	0.456[a]		0.045[a]
			0.071[b]	0.129[b]			0.684[b]
Snowden	55	16.9 ± 0.1	67.1 ± 0.1	73.3 ± 0.1	8.9 ± 0.2	46.6 ± 0.1	68.0 ± 0.3
	71	17.2 ± 0.3	65.0 ± 0.1	71.0 ± 0.3	9.8 ± 0.7	45.5 ± 0.1	65.7 ± 1.0
	91	17.8 ± 0.1	64.7 ± 0.1	70.0 ± 0.1	10.0 ± 0.4	45.9 ± 0.0	65.1 ± 0.1
	112	18.1 ± 1.0	65.1 ± 0.1	70.3 ± 0.2	9.9 ± 0.5	47.4 ± 2.0	64.7 ± 0.6
	124	18.0 ± 0.1	65.0 ± 0.2	70.0 ± 0.0	10.2 ± 0.4	46.5 ± 0.4	63.9 ± 0.0
	p-value	0.178[a]	0.000[a]	0.000[a]	0.164[a]	0.010[a]	0.005[a]
			0.104[b]	0.184[b]		0.045[b]	0.141[b]

[a] From all starches of same cultivar.
[b] From all starches of same cultivar excluding the shortest growth time.
[c] From all starches of same cultivar excluding the first two harvest times.
[d] Not available due to insufficient slope.

temperature in the thermogram of retrograded starch. Compared to the other starches, Shepody starch showed a slightly higher retrogradation peak temperature, but slightly lower retrogradation enthalpy. Phase transition temperature and enthalpy of gelatinization and retrogradation might be influenced by the length of double helices in the crystallites (Cooke & Gidley, 1992).

3.8. Starch pasting properties during potato growth

The starch pasting properties of all three potato cultivars with different growth times are presented in Table 5. Fig. 3 shows the pasting curves of Superior starch during potato growth. Shepody and Snowden starches had similar pasting profiles as Superior. The peak viscosity increased as growth time increased, however, the final viscosity decreased as growth progressed.

Starch pasting properties were greatly influenced by growth time. At the shortest growth time, the peak viscosity of starch pasting was 3256, 4077, and 3968 cP for Superior, Shepody, and Snowden potatoes, respectively. The peak viscosity of starch pasting increased as potato growth time increased. For starch with the longest growth time, the peak viscosity was 6858, 7217, and 7567 cP for Superior, Shepody, and Snowden potatoes, respectively, and about two times higher than that of the shortest growth time. At the shortest growth time, the final viscosity of starch pasting was 3769, 4021, and 3897 cP for Superior, Shepody, and Snowden potatoes, respectively. It decreased as potato growth time increased. The final viscosity of starch pasting at the longest growth time was 2047, 2738, and 1959 cP for Superior, Shepody, and Snowden potatoes, respectively, and about half that of the shortest growth time potato. Pasting temperature was the highest when potatoes were harvested at the earliest time for all three cultivars. It was 71.0, 71.8, and 70.2 °C for Superior, Shepody, and Snowden potatoes, respectively. The pasting temperature decreased as potato growth time increased. At the final harvest time, it was 67.0, 67.9, and 66.1 °C for Superior, Shepody, and Snowden potatoes, respectively. Shepody potato starch shows a higher pasting temperature, higher peak viscosity and higher final viscosity than that of Snowden and Superior starches. The different pasting properties of starch from different cultivars may be due to the difference in granular size, phosphorous content and amylose content of starch granules.

Starch from potatoes with shorter growth time resulted in lower peak viscosity, higher final viscosity and higher pasting temperature. Results from starch granular size measurement in this study indicate that the size of starch granules is the smallest at the shortest growth time of potato. The smaller size of starch granules seemed to contribute to

Table 5
Pasting properties of starch from different potato cultivars during growth by RVA

Cultivar	Growth time (day)	Peak viscosity (cP)	Final viscosity (cP)	Pasting temperature (°C)
Superior	48	3256.0 ± 0.0	3768.5 ± 43.1	71.0 ± 0.3
	56	3893.0 ± 11.3	3000.0 ± 43.8	69.0 ± 0.3
	64	4315.0 ± 30.4	2486.0 ± 11.3	67.4 ± 0.3
	84	6657.0 ± 22.6	2098.5 ± 2.1	66.8 ± 0.0
	117	6858.0 ± 34.7	2046.5 ± 2.1	67.0 ± 0.4
Shepody	55	4077.0 ± 91.9	4020.5 ± 17.7	71.8 ± 0.3
	71	5866.0 ± 99.0	2821.5 ± 12.0	68.4 ± 0.0
	91	7438.0 ± 36.1	2889.5 ± 5.0	68.7 ± 0.0
	112	7518.0 ± 28.3	2653.5 ± 9.2	68.4 ± 0.1
	124	7217.0 ± 60.8	2737.5 ± 13.4	67.9 ± 0.0
Snowden	55	3968.0 ± 35.4	3896.5 ± 17.7	70.2 ± 0.4
	71	6846.0 ± 55.2	2379.5 ± 24.8	67.3 ± 0.3
	91	7725.0 ± 74.3	2100.0 ± 15.6	66.2 ± 0.2
	112	7373.0 ± 118.8	2010.5 ± 55.9	66.2 ± 0.2
	124	7567.0 ± 0.0	1959.0 ± 11.3	66.1 ± 0.1

the lower peak viscosity of these starches according to Madsen and Christensen (1996) due to the lowest swelling factor (Fig. 2). Many other factors, including amylose content and phosphate ester content (Wiesenborn, Orr, Casper, & Tacke, 1994), may also influence the pasting properties of starch. At the shortest growth time, amylose content of the isolated starches was the highest compared to later harvest tubers for the three selected cultivars. The higher amylose content of the starch granules could be one of several factors contributing to low peak viscosity, high final viscosity and high pasting temperatures. In the three selected potato cultivars, the order of phosphorous content in starch granules is Shepody > Snowden > Superior at the shortest and longest growth time of potato. The order of final viscosity of starch paste is Shepody > Snowden > Superior at the shortest and longest growth time of potato. The lower phosphorous content of Superior potato starch resulted in the lower peak and final viscosity of starch paste.

4. Conclusions

Starch content of potato tubers varied during growth. The highest starch content was found when potato growth time was around 2–3 months. Potatoes from Shepody and Snowden cultivars had a higher starch content than Superior. X-ray diffraction pattern of starch granule was not affected by potato growth time. Apparent amylose content did not change significantly during growth except for Shepody. Swelling factor of starch was greatly influenced by potato growth time. Desired functional properties of starch could be achieved by the selection of potato cultivar and controlling growth time. Starch from the

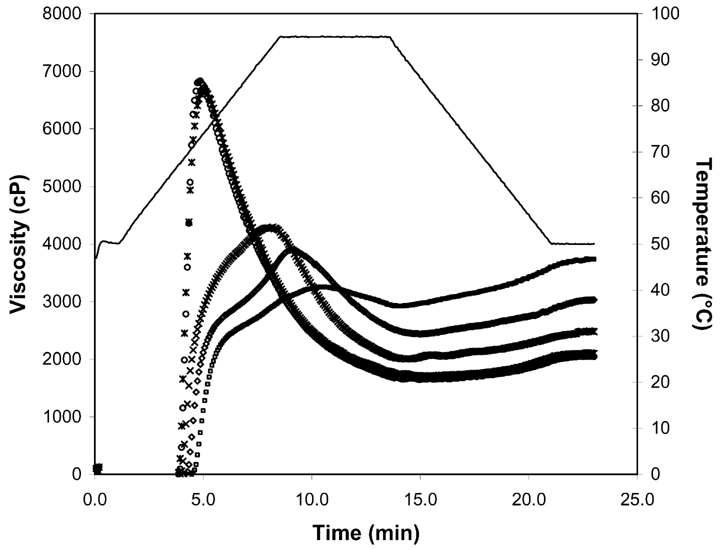

Fig. 3. The RVA pasting curves of Superior potato starch during potato growth at 48 (□), 56 (◇), 64 (×), 84 (∗), and 117 (○) days.

Shepody potato cultivar had the highest final viscosity, highest peak temperature and the lowest enthalpy of gelatinization and retrogradation. Shortest growth time potatoes resulted in a lower swelling factor, higher amylose content and higher gelatinization temperature, pasting temperature and final viscosity of their starches.

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