Available online at www.sciencedirect.com
ScienceDirect
Food Chemistry 105 (2007) 897–907
Food Chemistry
www.elsevier.com/locate/foodchem

Physicochemical properties of dry matter and starch from potatoes grown in Canada

Qiang Liu [a,*], Richard Tarn [b], Dermot Lynch [c], Neil M. Skjodt [d]

[a] Food Research Program, Agriculture and Agri-Food Canada (AAFC), 93 Stone Road W., Guelph, Ontario, Canada N1G 5C9
[b] Potato Research Centre, AAFC, P.O. Box 20280, Fredericton, New Brunswick, Canada E3B 4Z7
[c] Lethbridge Research Centre, AAFC, P.O. Box 3000, Lethbridge, Alberta, Canada T1J 4B1
[d] Department of Medicine, University of Alberta, 2E4.43 Walter C. MacKenzie, Health Sciences Centre, Edmonton, Alberta, Canada T6G 2B7

Received 26 January 2007; received in revised form 10 April 2007; accepted 16 April 2007

Abstract

In this study dry matter and starch were isolated from three potato cultivars (AC Stempede Russet, Russet Burbank and Karnico) grown at two locations (Fredericton and Benton) in New Brunswick, Canada. The chemical composition including total starch, dietary fibre, free glucose and protein content in potato dry matter and apparent amylose and total phosphorus content in potato starch were determined. Differential scanning calorimetry (DSC) was used to determine the thermal properties of gelatinization and retrogradation of potato dry matter and starch. The pasting properties of potato dry matter and starch were investigated by rapid visco analyzer (RVA). The resistant starch measurement method was employed to evaluate the digestibility *in vitro* of native and gelatinized potato starch. Molecular characteristics including chain length and chain length distribution of potato starch were also analyzed using high performance anion exchange chromatography (HPAEC). The analytical results suggest that differences in chemical composition and molecular chain length of potato starch may contribute to different functional properties of potato dry matter and starch of individual cultivars.

Keywords: Physicochemical properties; Potato dry matter; Potato starch; Chemical compositions; Morphology; Resistant starch *in vitro*; Gelatinization; Retrogradation; Pasting; Chain length

1. Introduction

Potato is a staple food in western countries including Canada. The potato tuber contains carbohydrates, proteins, ash, ascorbic acid and other vitamins, phenolic substances, and nucleic acids. The composition of potato varies with the cultivar, growing area, and fertilization regime. Starch content in potatoes varies with cultivar and plant growth stage, and ranges between 66% and 80% on a dry weight basis (Li, Scanlon, Liu, & Coleman, 2006). Year to year variation in content and functional properties of the starch of the same cultivar have also been reported (Svegmark et al., 2002; Weisenborn, Orr, Casper, & Tacke, 1994). Potato starch is a polysaccharide composed of a mixture of two biopolymers, amylose, a linear fraction, and amylopectin, a highly branched fraction. Potato starch also contains a higher phosphorus content than other plant starches (~0.08% in potato starch, ~0.02% in corn starch, ~0.01% in waxy maize starch, and ~0.01% in Tapioca starch) (Li et al., 2006). There is an absence of internal lipids and proteins in potato starch granules. Native potato starch shows a B-type X-ray diffraction pattern with about 28% crystallinity (Zobel, 1988). The granular structure of the starch is essentially determined by genetic factors that govern starch biosynthesis (Guilbot & Mercier, 1985).

In recent years, the glycemic index (GI) (Jenkins et al., 1981) has been transformed from a potentially useful tool in planning diets for diabetic patients, to a promising strategy for the prevention of diabetes, dyslipidemia, cardiovascular disease, and even certain cancers in the general population.

* Corresponding author. Tel.: +1 519 780 8030; fax: +1 519 829 2600.
E-mail address: liuq@agr.gc.ca (Q. Liu).

0308-8146/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.foodchem.2007.04.034

Decreasing sugar and/or digestible starch as well as lipid intake and increasing dietary fibre intake are widely accepted dietary strategies for the prevention of these diseases.

Raw potato starch is an enzyme-resistant starch which is associated with the large granule size, higher phosphate content, B-type crystalline, different chain length, and chain length distribution, as well as different molecular weight and weight distribution, as compared to cereal and other starches (Jane, Wong, & McPherson, 1997). However, when potatoes are cooked for consumption, starch is gelatinized and becomes susceptible to hydrolysis by α-amylase (Englyst & Cummings, 1987). Starch can be divided into three categories based on nutritional classification: rapidly digestible starch, slowly digestible starch, and resistant starch (Englyst & Kingman, 1990). Resistant starch is not hydrolysed in the small intestine and enters the colon for fermentation (Englyst & Kingman, 1990). In general, starch in a cooked potato is rapidly digested and only a small residue remains undigested. However, linear starch molecules such as amylose in the gelatinized starch system are able to retrograde to form a single or double helical structure that is highly resistant to hydrolysis by α-amylase (Englyst & Cummings, 1987; Miles, Morris, Orford, & Ring, 1985; Ring, Gee, Whittam, Orford, & Johnson, 1988). Thus, it is very important to understand this characteristic of potato starch since it plays a key role in the digestibility of potato products and the glycemic response in human subjects. The degree of starch digestion in potato products depends on potato composition as well as different processing and storage conditions. The carbohydrate content of potato varies widely between cultivars (Burton, 1966). In recent GI studies for potato, Soh and Brand-Miller (1999) found no significant difference in GI between three cultivars (Desiree, Pontiac and Sebago) prepared by boiling, boiling and mashing, micro-waved, and baked.

The purposes of this study were (1) to investigate the chemical compositions, physicochemical and structural properties of potato dry matter and starch isolated from Canadian-grown potatoes and (2) to further understand the relationship between chemical composition, molecular characteristics, and digestibility *in vitro* of potato starch. In this study, the physicochemical properties of potato dry matter and starch were characterized using various analytical techniques such as differential scanning calorimetry (DSC), rapid visco-analyzer (RVA), and high performance anion exchange chromatography (HPAEC). These physicochemical properties include gelatinization, retrogradation, pasting properties and morphology, molecular chain length, and digestibility *in vitro*.

2. Materials and methods

2.1. Potato

Potato varieties used in this project were grown in the region of New Brunswick (Fredericton and Benton), Canada in 2003.

1. AC Stampede Russet (Fredericton 8 and Fredericton 23): AAFC variety (Lynch et al., 1999).
2. Russet Burbank (Benton 8 and Fredericton 19): most widely grown Northern American variety with high dry matter content.
3. Karnico (Fredericton 15 and Fredericton 27): AVEBE starch variety.

Potatoes were received from the Potato Research Centre, AAFC (Fredericton, New Brunswick). They were stored for 48 h (Food Research Program, AAFC, Guelph, Ontario) prior to isolating potato dry matter and starch.

All the chemicals and pancreatin (P-1625) were purchased from Sigma Chemical (Sigma Chemical CO., St. Louis, MO, USA). Thermostable α-amylase and amyloglucosidase were purchased from Megazyme (Megazyme E-AMGDF, Megazyme International Ireland Ltd., Bray, Ireland). Isoamylase (EN102, 68,000 U/mg protein) was obtained from Hayashibara Biochemical Laboratories, Inc. (Okayama, Japan).

2.2. Potato dry matter

Potato dry matter was obtained according to the method of Liu, Yada, and Arul (2002). After peeling and freeze-drying, the dry matter was ground and passed through a 250 μm sieve. The dry matter samples were kept in air-tight plastic bags at room temperature until further use.

2.3. Potato starch

Starch isolation was followed according to Liu, Weber, Currie, and Yada (2003). Dried starch was passed through a 125 μm sieve and packed in air-tight plastic bags at room temperature until further use.

2.4. Total starch content of potato dry matter

Total starch content of potato dry matter was determined based on AACC method 76.13 (AACC, 2000) with modification. Following the incubation period, the tubes were centrifuged. The supernatant (1 mL) was diluted with 2 mL of distilled water and the glucose content was subsequently measured using the YSI 2700 Biochemistry Analyzer (Yellow Springs, OH, USA). Control samples, which were not treated with the enzymes, were also included in the procedure to determine free glucose content. A regular maize starch was used as a standard in the experiment to ensure enzyme activity.

Starch content of potato dry matter was calculated as follows:

Starch content $= 0.9 \times$ (glucose content after incubation − blank's glucose content). The reported values are means of duplicate measurements.

2.5. Total free glucose content of potato dry matter

Free glucose content in potato dry matter was measured during the procedure of total starch content determination (see above) for the blank samples without enzyme hydrolysis. The reported values are means of duplicate measurements.

2.6. Total protein content of potato dry matter

Protein content of dry matter was determined using Thermoquest CE Instrument (NA 2100 Protein, ThermoQuest Italia S.P.A., Ann Arbor, MI, USA). The instrument determines the nitrogen content of the sample. Dry matter sample (30 mg) first underwent a controlled combustion then was energetically oxidized and reduced, producing a gas mixture that was subsequently passed through a chromatographic column. Pure eluted combustion gas passed through a thermoconductivity detector which generates an electrical output signal that was proportional to the amount of eluted gas. The nitrogen content was determined using software (Eager 200 for Windows™, Version 1.02, ThermoQuest Italia S.P.A., Ann Arbor, MI, USA). Protein content was calculated by multiplying the nitrogen content by a factor of 6.25. Atropine (4.84% N), DL-methionine (9.39% N), acetanilide (10.36% N), and nicotinamide (22.956% N) were used as standards to produce a standard curve. The reported values are means of duplicate measurements.

2.7. Total dietary fibre content of potato dry matter

Total dietary fibre content of potato dry matter was determined according to the AACC (2000) method 32-05 following the total dietary fibre assay procedure (Megazyme k-TDFR 01/05). The reported values are means of duplicate measurements.

2.8. Apparent amylose content of potato starch

Apparent amylose contents in potato starch were determined by iodine colorimetry according to Williams, Kuzina, and Hlynka (1970). The reported values are means of duplicate measurements.

2.9. Total phosphorous content of potato starch

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.

2.10. Scanning electron microscopy (SEM) of potato starch

SEM was performed on a Hitachi S-4500 filed emission scanning electron microscope (Hitachi Ltd., Tokyo, Japan) equipped with Quartz PCI digital image acquisition software (Quartz Imaging Corp., Vancouver, BC, Canada). The starch samples were sprayed on a metal plate previously covered with double-sided adhesive, and gold:palladium (60:40) coated using a Polaron SC500 sputter coater (Quorum Technologies, East Sussex, UK). The samples were examined at 5.0 kV accelerating voltage. Representative micrographs were taken for each sample at magnifications of 500×.

2.11. Differential scanning calorimetry (DSC)

Thermal analyses were performed using a differential scanning calorimeter (2920 modulated DSC; TA Instruments, New Castle, DE, USA) equipped with a refrigerated cooling system (RCS) for gelatinization and retrogradation of starch and dry matter.

Gelatinization: sample of potato starch and dry matter was weighed into high-volume pans. Distilled water was added using a micropipette to make suspensions with 70% moisture content. Sample weight was about 12 mg. Pan was sealed and equilibrated at least 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. The instrument was calibrated using indium and an empty pan as reference. The enthalpy (ΔH) of phase transitions was measured from the endotherm of DSC thermograms using software (Universal Analysis, Version 2.6D, TA Instruments, New Castle, DE, USA) based on the mass of dry solid. Peak temperature (T_p) of endotherms was also measured from DSC thermograms. These characteristics were used to compare gelatinization properties of potato dry matter and starch.

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, stored sample was heated from 5 to 180 °C at 10 °C/min. The enthalpy (ΔH) and peak temperature (T_p) of the endotherm were measured from DSC thermograms based on dry solid mass. The integration was performed using the same temperature range for potato starch and dry matter. These characteristics were used to compare retrogradation property of potato dry matter and starch. The reported values are the means of duplicate measurements.

2.12. Rapid visco™ analyzer (RVA)

Pasting properties of potato starch and dry matter were determined using a rapid visco™ analyzer RVA-4 (Newport Scientific Pty. Ltd, Warriewood, NSW, Australia). Sample concentration was 6% based on the mass of dry solid. Experiments were performed using the STD 2 profile (AACC, 2000), in which the sample was 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 obtained from pasting curves. The reported values are the means of duplicate measurements.

2.13. Resistant starch content in vitro

Native starch: isolated potato starch samples were treated with pancreatic α-amylase and amyloglucosidase (AMG) and then placed in a shaking water bath at 37 °C for 16 h incubation time. The resistant starch and non-resistant starch were measured based on Megazyme method with modification (AACC, 2000). The reported values are the means of duplicate measurements.

Gelatinized starch: gelatinized potato starches were obtained from the RVA samples. After RVA experiment, the gel was removed from the aluminum canister and dried overnight at 40 °C. The dry gel was ground using a ball mill and passed through a 125 μm sieve. The resistant starch content of gelatinized potato starch was determined by treatment with pancreatic α-amylase and amyloglucosidase (AMG) with incubation times of 20 and 120 min. The reported values are the means of duplicate measurements.

2.14. High performance anion exchange chromatography-pulsed amperometric detection (HPAEC-PAD)

Isoamylase debranched starch: selected potato starch was dispersed in 2 mL of 90% DMSO (5 mg/mL) by stirring in a boiling water bath for 20 min. After cooling, methanol (6 mL) was added with vortexing, and the tube placed in an ice bath for 30 min. The pellet, which was recovered by centrifugation (1000*g* for 12 min), was dispersed in 2 mL of 50 mM sodium acetate buffer (pH 3.5) by stirring in a boiling water bath for 20 min. Following equilibration of the tube at 37 °C, isoamylase (5 μL) was added. The sample was incubated at 37 °C with slow stirring for 22 h. The enzyme was inactivated by boiling for 10 min. An aliquot (200 μL) of the cooled debranched sample was diluted with 2 mL of 150 mM NaOH. The sample was filtered (0.45 μm nylon syringe filter) and injected into the HPAEC-PAD system (50 μL sample loop) (Dionex Corporation, Sunnyvale, CA, USA).

The HPAEC-PAD system consisted of a Dionex DX 600 equipped with an ED50 electrochemical detector with a gold working electrode, GP50 gradient pump, LC30 chromatography oven, and AS40 automated sampler (Dionex Corporation, Sunnyvale, CA, USA). The standard triple potential waveform was employed, with the following periods and pulse potentials: $T_1 = 0.40$ s, with 0.20 s sampling time, $E_1 = 0.05$ V; $T_2 = 0.20$ s, $E_2 = 0.75$ V; $T_3 = 0.40$ s, $E_3 = -0.15$ V. Eluents were prepared in distilled deionized water with helium sparging; eluent A was 500 mM sodium acetate in 150 mM NaOH, and eluent B was 150 mM NaOH. Linear components were separated on a Dionex CarboPac™ PA1 column with gradient elution (−5 min to 0 min, 40% A; 5 min, 60% A; 45 min, 80% A) at

Table 1
Chemical composition of potato dry matters and potato starch

Potato	Sample	Total starch[a] (TS) (%, w/w)	Mean[b] TS (%)	Total dietary fiber[a] (TDF) (%, w/w)	Mean TDF (%)	Total protein[a] (TP) (%, w/w)	Mean TP (%)	Total free glucose[a] (TFG) (%, w/w)	Mean TFG (%)	Apparent amylose[a] in starch (%, w/w)	Mean amylose (%, w/w)	Total phosphorus[a] in starch (%%, w/w)	Mean phosphorus (%%, w/w)
AC Stampede Russet	Fredericton 8	69.4 ± 0.2	70.5 ± 1.5	5.4 ± 0.1	5.2 ± 0.3	10.6 ± 0.4	9.7 ± 1.3	2.4 ± 0.3	3.3 ± 1.2	30.4 ± 0.4	29.7 ± 1.0	8.2 ± 0.5	8.5 ± 0.4
	Fredericton 23	71.5 ± 0.4		5.0 ± 0.4		8.8 ± 0.6		4.1 ± 0.6		29.0 ± 1.2		8.8 ± 0.5	
Karnico	Fredericton 15	72.3 ± 0.3	72.4 ± 0.1	5.9 ± 0.0	5.6 ± 0.4	5.4 ± 0.6	7.1 ± 2.4	5.3 ± 0.4	5.2 ± 0.2	32.8 ± 0.4	3.3 ± 0.6	4.9 ± 0.1	4.6 ± 0.4
	Fredericton 27	72.4 ± 1.1		5.2 ± 0.0		8.8 ± 0.2		5.0 ± 3.0		33.7 ± 0.2		4.3 ± 0.1	
Russet Burbank	Benton 8	71.9 ± 0.9	71.6 ± 0.5	5.0 ± 0.2	5.3 ± 0.4	8.7 ± 0.0	9.0 ± 0.4	6.1 ± 0.4	6.0 ± 0.1	32.8 ± 0.8	32.5 ± 0.5	7.3 ± 0.5	7.1 ± 0.4
	Fredericton 19	71.2 ± 0.3		5.7 ± 0.1		9.2 ± 0.5		5.9 ± 0.8		32.1 ± 1.5		6.8 ± 0.4	

[a] Value denotes means ± standard derivation.
[b] Obtained from the mean value of two duplicates of two dry matter samples or two starch samples with same potato variety.

a column temperature of 26 °C and a flow rate of 1 mL/min. A CarboPac™ PA1 guard column was installed in front of the analytical column. Data were collected using Chromeleon software, version 6.50 (Dionex Corporation, Sunnyvale, CA). The weight fraction of DP 6–12, 13–24, 25–36 and 37–58 was measured based on the area of peaks. The reported values are the means of duplicate measurements.

3. Results and discussion

3.1. Chemical composition of potato dry matter

From Table 1, total starch, dietary fibre, protein, and free sugar content of AC Stampede Russet potato dry matter were 70.5%, 5.2%, 9.7%, and 3.3%, respectively (based on mean value from two potatoes with same variety). Total

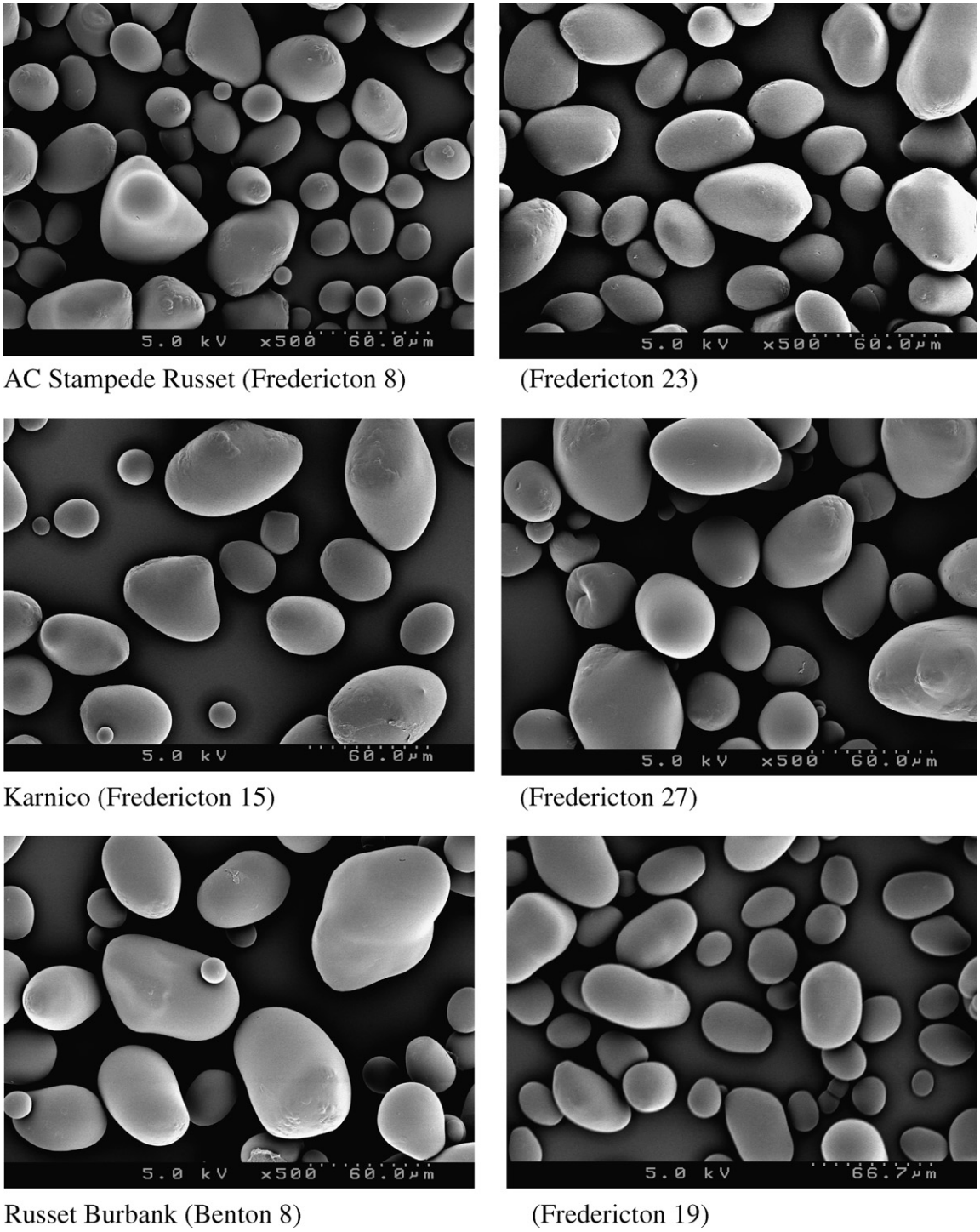

Fig. 1. Scanning electron microscopy (SEM) of potato starch.

starch, dietary fibre, protein, and total free sugar content of Russet Burbank potato dry matter were 71.6%, 5.3%, 9.0%, and 6.0%, respectively. Total starch, dietary fibre, protein, and total free sugar content of Karnico potato dry matter were 72.4%, 5.6%, 7.1%, and 5.2%, respectively. It seems that the protein content of AC Stampede Russet is not much different from that of Russet Burbank. The difference of total dietary fibre content among the samples is small. However, total starch content and free glucose was lower in AC Stampede Russet dry matter than in that of Russet Burbank.

3.2. Chemical composition of potato starch

From Table 1, apparent amylose content was 29.7%, 33.3%, and 32.5% for starch isolated from AC Stampede Russet, Karnico and Russet Burbank potato, respectively. Total phosphorus content was 8.5, 4.6, and 7.1×10^{-2}% for starch isolated from AC Stampede Russet, Karnico, and Russet Burbank potato, respectively. Starch from AC Stampede Russet had slightly lower apparent amylose content and higher phosphorus content than that from Russet Burbank. However, starch from Karnico contained a much lower phosphorus content than starch from the other two cultivars.

3.3. Scanning electron microscopy (SEM) of potato starch

Scanning electron micrographs of selected potato starch are shown in Fig. 1. Potato starch exists in the form of granules, which differ in size and shape in the three cultivars (Fig. 1). They are generally voluminous and oval shaped. Some potato starch also showed a polygonal shape. Although the overall morphology is similar for the potato starch of the three cultivars, the size and size distribution appear to be unique. However, differences in morphology were observed in the starch isolated from tubers of same cultivar (images not shown). Since enzyme hydrolysis took place first on the surface of starch granules, the morphology of starch could be one of important factors influencing starch functionality such as digestibility *in vitro*. Further investigation is planned to determine the size and size distribution of starch as a function of cultivar.

3.4. Gelatinization of potato dry matter and starch

When dry matter and starch were heated in the presence of excess water, starch gelatinization occurred as shown in Fig. 2a. All the dry matter and starch samples had similar DSC profile. The endothermic peak represents the phase transition of starch from ordered granular structure (e.g. double helices) to random coil state during starch gelatinization. Table 2 presents the gelatinization properties of potato dry matter and starch.

As shown in Fig. 2a, the endothermic peak of potato dry matter mainly reflected starch gelatinization. For dry matter the peak temperature of gelatinization was 69.1, 68.9, and 68.5 °C and the enthalpy was 13.2, 13.3, and 11.9 J/g for AC Stampede Russet, Karnico, and Russet Burbank potato, respectively. For starch the peak temperature of gelatinization was 66.6, 66.8, and 65.7 °C and the enthalpy was 17.9, 18.4, and 17.4 J/g for AC Stampede Russet, Karnico, and Russet Burbank potato, respectively. The peak temperature of starch gelatinization in potato dry matter was about 3 °C higher than pure starch. It could be interpreted that water availability to starch was reduced in the dry matter–water system by the existence of other components (e.g. proteins and fibres), partially inhibition of water migration, and interaction between water and other components. Thus, it resulted in increasing peak temperature in order to gelatinize starch. In addition, the range (onset to end temperature) of phase transition (endothermic peak) in potato dry matter was also wider than that of pure starch (data not shown). Gelatinization enthalpy of starch in potato dry matter was much lower than for pure starch. This could be due to smaller interaction between starch and water in dry matter water system than in pure starch water system.

Overall, AC stampede Russet had similar gelatinization property to Russet Burbank and Karnico for both dry

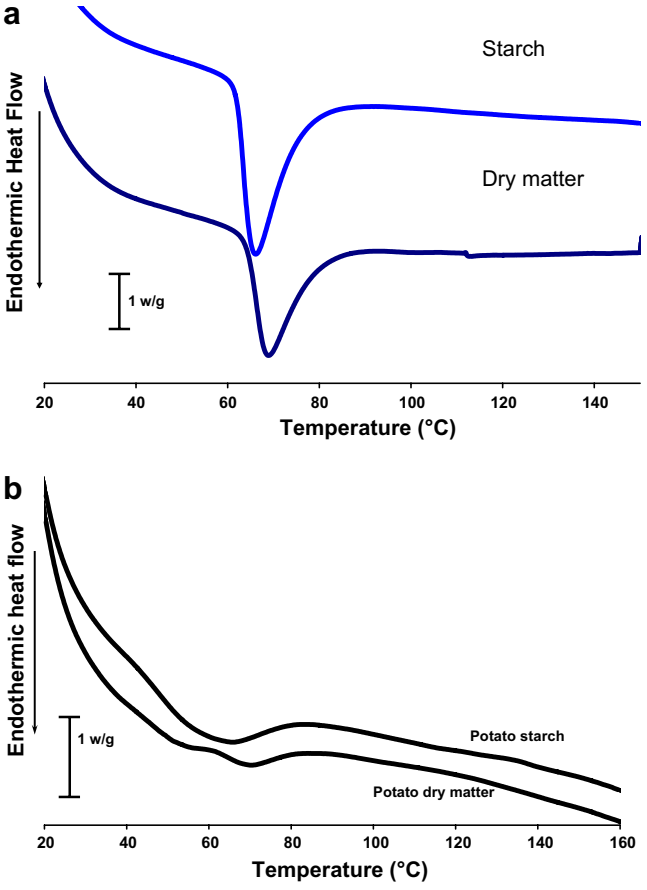

Fig. 2. DSC thermograms of (a) potato dry matter and starch of AC Stampede Russet heated in the presence of excess water as a function of temperature and (b) gelatinized 30% potato dry matter and starch from AC Stampede Russet potato after 2 weeks storage.

Table 2
The gelatinization properties of potato dry matter and starch

Potato variety	Potato sample	T_p[a] (°C)		Mean[b] T_p (°C)		ΔH[a] (J/g)		Mean[b] ΔH (J/g)	
		Dry matter	Starch	Dry matter	Starch	Dry matter	Starch	Dry matter	Starch
AC Stampede Russet	Fredericton 8	68.8 ± 0.0	66.9 ± 0.5	69.1 ± 0.4	66.6 ± 0.4	13.0 ± 0.0	18.3 ± 0.4	13.2 ± 0.2	17.9 ± 0.6
	Fredericton 23	69.3 ± 0.2	66.3 ± 0.2			13.3 ± 0.4	17.4 ± 1.6		
Karnico	Fredericton 15	68.9 ± 0.2	66.5 ± 0.2	68.9 ± 0.0	66.8 ± 0.4	13.8 ± 0.2	17.9 ± 0.1	13.3 ± 0.7	18.4 ± 0.7
	Fredericton 27	68.9 ± 0.5	67.0 ± 0.2			12.8 ± 0.9	18.9 ± 1.0		
Russet Burbank	Benton 8	67.5 ± 0.0	64.9 ± 0.1	68.5 ± 1.4	65.7 ± 1.1	12.2 ± 2.2	17.1 ± 0.4	11.9 ± 0.5	17.4 ± 0.4
	Fredericton 19	69.5 ± 1.1	66.5 ± 0.4			11.5 ± 1.3	17.7 ± 0.4		

[a] Value denotes means ± standard derivation.
[b] Obtained from the mean value of two dry matter samples or two starch samples with same potato variety.

matter and starch. Only slightly lower enthalpy was observed for dry matter of Russet Burbank potato. Starch gelatinization is dependent on the molecular structure, crystalline structure, moisture content, foreign components other than starch and water, and processing conditions. The similar gelatinization property indicates these potato starches had similar molecular structure, double helix content, and crystalline structure (Cooke & Gidley, 1992). Different chemical compositions in potato dry matter and starch (Table 1) seem to have less impact on starch gelatinization temperature and enthalpy.

3.5. Thermal properties of retrograded potato dry matter and starch

Starch retrogradation has been used to describe changes in physical behavior following gelatinization. It is the process that occurs when starch molecules reassociate and form an ordered structure during storage. In an initial step, two chains may associate. Ultimately, under favourable conditions, a crystalline order appears and physical phase separation occurs (Atwell, Hood, Lineback, Varriano-marston, & Zobel, 1988). New ordered structure of retrograded starch contributes to enzyme resistance of starch (Englyst, Kingman, & Cummings, 1992). Fig. 2b shows the thermograms of retrograded AC Stampede Russet potato dry matter and starch after 2 week storage. All the retrograded dry matter and starch samples had similar DSC profile as Fig. 2b. The thermal transition took place at high temperature with narrow temperature range for retrograded potato dry matter compared to retrograded potato starch. The peak temperature and enthalpy of retrograded potato dry matter and starch from DSC thermogram are presented in Table 3. AC Stampede Russet potato shows similar thermal properties of retrogradation to Russet Burbank and Karnico potatoes. The peak temperature was 65.3 and 62.0 °C and the enthalpy was 7.7 and 10.1 J/g solid content for retrograded AC Stampede Russet dry matter and starch, respectively. The peak temperature was 63.3 and 61.3 °C, and the enthalpy was 7.9 and 8.7 J/g solid content for retrograded Russet Burbank dry matter and starch, respectively. The peak temperature was 64.9 and 61.9 °C, and the enthalpy was 7.9 and 9.9 J/g solid content for retrograded Karnico dry matter and starch, respectively. Again, similar thermal properties of retrograded potato dry matter and starch indicate these potato starches have similar structure. However, as presented in Table 3, the variation (standard derivation) of T_p and ΔH for potato dry matter between the samples is larger than that of potato starch. This indicates that other components in the potato dry matter interfere with starch retrogradation differently in potato dry matter water system.

3.6. Pasting properties of potato dry matter and starch

Fig. 3 shows the RVA profiles of AC Stampede Russet potato dry matter and starch. The pasting properties of dry matter and starch are shown in Table 4.

Table 3
The thermal properties of retrograded potato dry matter and potato starch

Potato variety	Potato sample	T_p[a] (°C)		Mean[b] T_p (°C)		ΔH[a] (J/g)		Mean[b] ΔH (J/g)	
		Dry matter	Starch	Dry matter	Starch	Dry matter	Starch	Dry matter	Starch
AC Stampede Russet	Fredericton 8	66.5 ± 1.7	61.8 ± 1.6	65.3 ± 1.7	62.0 ± 0.3	6.6 ± 0.4	10.7 ± 1.1	7.7 ± 1.5	10.1 ± 0.8
	Fredericton 23	64.1 ± 1.3	62.2 ± 1.2			8.7 ± 0.6	9.5 ± 0.2		
Karnico	Fredericton 15	65.9 ± 0.8	62.1 ± 0.6	64.9 ± 1.4	61.9 ± 0.4	7.7 ± 0.2	10.0 ± 0.1	7.9 ± 0.2	9.9 ± 0.2
	Fredericton 27	63.9 ± 0.5	61.6 ± 0.4			8.0 ± 0.5	9.7 ± 0.1		
Russet Burbank	Benton 8	63.9 ± 0.7	61.8 ± 0.7	63.3 ± 0.8	61.3 ± 0.8	7.8 ± 0.6	9.5 ± 0.8	7.9 ± 0.1	8.7 ± 1.1
	Fredericton 19	62.7 ± 1.1	60.7 ± 3.5			8.0 ± 0.1	7.9 ± 0.7		

[a] Value denotes means ± standard derivation.
[b] Obtained from the mean value of two dry matter samples or two starch samples with same potato variety.

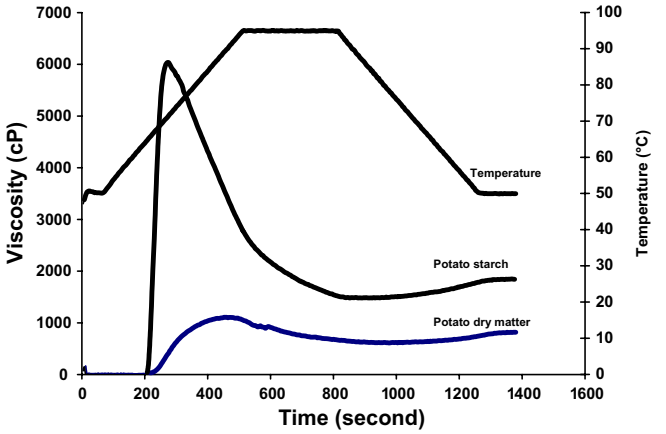

Fig. 3. RVA profiles of AC Stampede Russet potato dry matter and starch.

All potato starches and potato dry matters showed similar RVA profiles as Fig. 3. From Table 4, the pasting temperature was between 62.4 and 63.5 °C for the dry matter of the three cultivars and between 60.8 and 62.0 °C for the starch. Peak viscosity of dry matter paste was 1131, 1301 and 1218 cP for AC Stampede Russet, Karnico, and Russet Burbank, respectively. Large difference between 840 and 1314 cP in the final viscosity was observed for potato dry matter paste in three different potato varieties (Table 4). The lowest of peak viscosity and the lowest final viscosity of potato dry matter paste were observed for AC Stampede Russet.

For starch paste, the highest peak viscosity was 5835 cP from Russet Burbank and the lowest peak viscosity of potato starch paste was 4635 cP from Karnico. The much lower peak viscosity of potato starch from Karnico potato could be due to the presence of the lowest phosphorus content in this starch granule (Table 1). However, the effect of phosphorus content in final viscosity is different compared to peak viscosity. The highest final viscosity of potato starch paste was 1950 cP from Karnico and the lowest final viscosity of potato starch paste was 1689 cP for AC Stampede Russet. This is due to the highest apparent amylose content in Karnico potato starch and the lowest apparent amylose content in AC Stampede potato starch (Table 1). In a starch gel system, the higher amylose content increases retrogradation. As the system is subsequently cooled, reassociation between starch molecules, especially amylose, occurs to various degrees.

From the result in Table 4, the difference was very small for peak and final viscosity of potato starch paste between AC Stampede Russet and Russet Burbank. However, a slightly high standard deviation was obtained for potato starch isolated from the same cultivar but with different growing environments (Table 4). Although the overall pasting properties of AC Stampede Russet potato starch are similar to that of Russet Burbank, the pasting profiles and properties of potato dry matter were different from that of starch. Since potato dry matter contained starch,

Table 4
Pasting properties of potato dry matter and potato starch

Potato Variety	Potato sample	$T^{a}_{pasting}$ (°C)		Mean[b] T_p		Peak viscosity[a] (V_p) (cP)		Mean[b] V_p		Final viscosity[a] (V_f) (cP)		Mean[b] V_f	
		Dry matter	Starch	Dry matter	Starch	Dry matter	Starch	Dry matter	Starch	Dry matter	Starch	Dry matter	Starch
AC Stampede Russet	Fredericton 8	63.4 ± 0.3	62.0 ± 0.0	63.4 ± 0.0	61.4 ± 0.9	1096 ± 18	6016 ± 28	1131 ± 50	5782 ± 331	804 ± 20	1828 ± 21	840 ± 51	1689 ± 197
	Fredericton 23	63.4 ± 0.3	60.7 ± 0.0			1166 ± 7	5548 ± 35			876 ± 13	1550 ± 11		
Karnico	Fredericton 15	63.8 ± 0.3	61.6 ± 0.0	63.5 ± 0.4	62.0 ± 0.6	1232 ± 18	5083 ± 17	1301 ± 98	4635 ± 634	1157 ± 2	1848 ± 11	1119 ± 54	1950 ± 144
	Fredericton 27	63.2 ± 0.1	62.4 ± 0.0			1370 ± 7	4186 ± 190			1080 ± 13	2051 ± 2		
Russet Burbank	Benton 8	61.8 ± 0.3	60.4 ± 0.1	62.4 ± 0.8	60.8 ± 0.6	1264 ± 12	6508 ± 9	1218 ± 65	5835 ± 952	1448 ± 62	1734 ± 23	1314 ± 190	1700 ± 49
	Fredericton 19	62.9 ± 0.0	61.2 ± 0.0			1172 ± 8	5162 ± 74			1179 ± 13	1665 ± 18		

[a] Value denotes means ± standard derivation.
[b] Obtained from the mean value of two dry matter samples or two starch samples with same potato variety.

non-starch polysaccharides, proteins, free sugars, and other minor components, those non-starch components interacted with water and limited starch swelling in the dry matter water system. Therefore, it resulted in higher pasting temperature, much lower peak viscosity and final viscosity in dry matter pastes compared to potato starch paste. We also observed that the impact of phosphorus content of starch granule on peak viscosity was small in the dry matter paste compared to pure starch paste. As to the large difference in final viscosity between AC Stampede Russet and Russet Burbank dry matter (Table 4), the lower starch content in AC Stampede Russet dry matter could result in difference in final viscosity of dry matter paste.

3.7. Starch digestibility (resistant starch in vitro)

Resistant starch contents in native and gelatinized starch are shown in Table 5. From Table 5, native potato starch from AC Stampede Russet showed slightly lower resistant starch content compared to other starches, although the difference was small. It may due to its slightly lower apparent amylose content in potato starch granules from AC Stampede Russet. It appears that lower phosphorus content in starch granules resulted in higher resistant starch among these potato starches.

From Table 5, after 20 min enzymatic hydrolysis, gelatinized potato starch from AC Stampede Russet showed slightly higher resistant starch than that of Russet Burbank. In other words, AC Stampede Russet potato had a lower amount of rapidly digestible starch than that of Russet Burbank. Rapidly digestible starch is starch that is rapidly and completely digested in the small intestine. It can be determined after 20 min enzymatic hydrolysis *in vitro* (Englyst et al., 1992). Rapidly digestible starch is associated with greater and more rapid elevation of postprandial plasma glucose and insulin, and is linked to diabetes, coronary heart disease, and with the aging process (Englyst et al., 1992).

After 2 h incubation, potato starch from AC Stampede Russet also had higher resistant starch than that of Russet Burbank. Those digestible starches between 20 min and 2 h incubation time are considered as slowly digestible starch. It can be determined after 120 min enzymatic hydrolysis *in vitro* (Englyst et al., 1992). Slowly digestible starch is starch that is completely but more slowly digested in the small intestine. Slowly digestible starch has an attenuated influence on postprandial plasma glucose and insulin levels, and is nutritionally the more desirable form of starch (Jenkins et al., 1981). In this study, data showed that gelatinized potato starch from AC Stampede Russet had lower amount of digestible starch (higher amount of resistant starch) than that of Russet Burbank.

3.8. Chain length profile of potato starch

Table 6 shows the weight fraction of chain length in selected potato starch. Potato starch from AC Stampede Russet had a lower weight fraction of short chains (DP 6–12) than that of Russet Burbank and Karnico. However, it contained higher intermediate chains (DP 13–24) than that of Russet Burbank and Karnico. The difference in chain length and chain length distribution between AC Stampede Russet and Russet Burbank potato starches could contribute to their difference in resistant starch content after cooking. The longer chain length and higher amount of longer chain fractions in the starch molecule play a role in starch retrogradation. The higher degree of starch retrogradation could reduce the degree of enzymatic hydrolysis of starch (Englyst et al., 1992). Since Karnico potato starch contained higher apparent amylose content and the higher amount of long chain (DP > 37), it resulted in the highest resistant starch content in its granular and gelatinized forms.

It is evident that starch functionality such as pasting properties and digestibility *in vitro* is greatly influenced by chemical composition, and the granular structure and molecular chain length of potato starch. The ratio of amylose and amylopectin, and chain length of starch molecules are considered the key factors in developing resistant starch

Table 5
Resistant starch (RS) of native potato starch and gelatinized potato starch after 20 min and 2 h incubation time by enzymes (pancreatic α-amylase and amyloglucosidase)

Potato variety	Starch sample	RS[a] of native potato starch (%, w/w)	Mean[b] RS (%, w/w)	RS[a] (%) of gelatinized starch after 20 min incubation	Mean[b] RS after 20 min	RS[a] (%) of gelatinized starch after 120 min incubation	Mean[b] RS (%) after 120 min
AC Stampede Russet	Fredericton 8	68.4 ± 0.9	67.9 ± 0.7	5.0 ± 0.1	4.9 ± 0.1	3.7 ± 0.1	3.3 ± 0.6
	Fredericton 23	67.4 ± 1.9		4.8 ± 0.1		2.9 ± 0.0	
Karnico	Fredericton 15	72.3 ± 0.0	72.6 ± 0.4	5.2 ± 1.9	5.6 ± 0.5	3.3 ± 0.0	3.6 ± 0.4
	Fredericton 27	72.9 ± 1.3		5.9 ± 0.2		3.8 ± 0.3	
Russet Burbank	Benton 8	69.1 ± 0.9	69.8 ± 0.9	3.4 ± 0.1	4.0 ± 0.8	2.5 ± 0.0	2.7 ± 0.2
	Fredericton 19	70.4 ± 0.5		4.5 ± 0.0		2.8 ± 0.3	

[a] Value denotes means ± standard derivation.
[b] Obtained from the mean value of two native starch samples or two gelatinized starch samples with same potato variety.

Table 6
The chain length and its weight fraction in potato starch

Potato variety	Starch sample	DP 6–12 (%)	DP 13–24 (%)	DP 25–36 (%)	DP 37–54 (%)
AC Stampede Russet	Fredericton 23	26.8 ± 0.8	56.2 ± 0.1	12.8 ± 0.1	4.3 ± 0.6
	Fredericton 8	N/A	N/A	N/A	N/A
Karnico	Fredericton 15	28.5 ± 0.6	53.5 ± 0.2	12.9 ± 0.5	5.2 ± 0.3
	Fredericton 27	N/A	N/A	N/A	N/A
Russet Burbank	Fredericton 19	29.0 ± 1.5	53.4 ± 1.4	13.1 ± 1.1	4.5 ± 1.2
	Benton 8	N/A	N/A	N/A	N/A

N/A: not analyzed.

and slowly digestible starch. Resistant starch and slowly digestible starch could result in low glycemic indices of food products. Although the glycemic index differ between potato cultivars and can be modified by the processing methods of food products; many other factors such as the other components of the meal and a previously eaten meal could also influence the glycemic index (Lynch et al., in press). Future research should be focused on the identification of the genotypes/germplasm with high amylose content and special branch structure of amylopectin in potato starch in order to develop low glycemic index potato cultivars, and to understand the new starch in the cultivar.

4. Conclusions

The physicochemical properties of potato dry matter and starch vary with cultivar as well as with individual tubers of the same cultivar grown in Canada. Lower free glucose content and slightly lower starch content and similar protein content were found in dry matter of AC Stampede Russet compared to Russet Burbank. The lowest peak viscosity and the lowest final viscosity of potato dry matter paste were obtained from AC Stampede Russet potato. However, starch from AC Stampede Russet potato had a higher total phosphorus content, lower apparent amylose content, and a lower weight fraction of short chain lengths as well as a higher weight fraction of intermediate chain lengths. Starch from AC Stampede Russet potato showed lower slowly digestible and quickly digestible starch content in gelatinized starch compared to that from Russet Burbank. Differences in amylose content, phosphorus content, and weight fractions of chain lengths as well as morphology in the starch, were the factors for different starch digestibility (resistant starch *in vitro*). They also contribute to different functional properties such as gelatinization, retrogradation and pasting of potato dry matter, and starch.

Acknowledgements

The authors thank Mrs. Elizabeth Donner and Miss Rajinder Kaur for their technical support. This is scientific publication S270 of the Food Research Program, Agriculture and Agri-Food Canada, Guelph, Ontario.

References

AACC (2000). *Approved methods* (10 ed.). St. Paul, MN: American Association of Cereal Chemist.

Atwell, W. A., Hood, L. F., Lineback, D. R., Varriano-marston, E., & Zobel, H. F. (1988). The terminology and methodology associated with basic starch phenomena. *Cereal Food World, 33*, 306–311.

Burton, W. G. (1966). *The potato* (2nd ed.). Wageningen, Holland: Veenman.

Cooke, D., & Gidley, M. J. (1992). Loss of crystalline and molecular order during starch gelatinization: origin of the enthalpic transition. *Carbohydrate Research, 227*, 103–112.

Englyst, H. N., & Cummings, J. H. (1987). Digestion of polysaccharides of potato in the small intestine of man. *American Journal Clinical Nutrition, 45*, 423–431.

Englyst, H. N., & Kingman, S. M. (1990). Dietary fibre and resistant starch. A nutritional categorization of plant polysaccharides. In D. Kritchevsky, C. Bonfield, & J. W. Anderson (Eds.), *Dietary fiber – Chemistry, physiology and health effects* (pp. 49–65). New York: Plenum Press.

Englyst, H. N., Kingman, S. M., & Cummings, J. H. (1992). Classification and measurement of nutritionally important starch fractions. *European Journal Clinical Nutrition, 46*, S33–S50.

Guilbot, A., & Mercier, C. (1985). Starch. In G. O. Aspinall (Ed.), *Polysaccharide*. New York: Academic Press, Inc.

Jane, J. L., Wong, K., & McPherson, A. E. (1997). Branch-structure difference in starch of A- and B-type X-ray patterns revealed by their Naegeli dextrins. *Carbohydrate Research, 300*, 219–227.

Jenkins, D. J. A., Wolever, T. M. S., Taylor, R. H., Barker, H., Fielden, H., Baldwin, J. M., et al. (1981). Glycemic index of foods: A physiological basis for carbohydrate exchange. *American Journal Clinical Nutrition, 34*, 362–366.

Li, X., Scanlon, M. G., Liu, Q., & Coleman, W. K. (2006). Processing and value addition. In J. Gopal & A. M. P. Khurana (Eds.), *Potato production improvement and post-harvest management* (pp. 523–555). New York: Haworth Press.

Liu, Q., Yada, R., & Arul, J. (2002). Characterization of thermal properties of potato dry matter–water system. *Journal Food Science, 67*(2), 560–566.

Liu, Q., Weber, E., Currie, V., & Yada, R. (2003). Physicochemical properties of starches during potato growth. *Carbohydrate Polymers, 51*(2), 213–221.

Lynch, D. R., Miller, C., Kawchuk, L., Schaupmeyer, C., Holley, J., Panford, J., et al. (1999). AC Stampede Russet: A high yielding oblong russet cultivar for the french and fry and fresh market. *American Journal Potato Research, 78*, 261–270.

Lynch, D. R., Liu, Q., Tarn, T. R., Bizimungu, B., Chen, Q., Harris, P., Chik, C. L., & Skjodt, N. M. (in press). Glycemic Index – A review and

implications for the potato industry. American Journal Potato Research.

Miles, M. J., Morris, V. J., Orford, P. D., & Ring, S. G. (1985). The roles of amylose and amylopectin in the gelation and retrogradation of starch. *Carbohydrate Research, 135*, 271–281.

Ring, S. G., Gee, J. M., Whittam, M., Orford, P., & Johnson, T. I. (1988). Resistant starch: Its chemical form in foodstuffs and effect on digestibility in vitro. *Food Chemistry, 28*, 97–109.

Soh, N. L., & Brand-Miller, J. (1999). The glycaemic index of potatoes: The effect of variety, cooking method and maturity. *European Journal Clinical Nutrition, 53*, 249–254.

Svegmark, K., Helmersson, K., Nilsson, G., Nilsson, P. O., Andersson, R., & Svensson, E. (2002). Comparison of potato amylopectin starches and potato starch – Influence of year and variety. *Carbohydrate Polymers, 47*, 331–340.

Thomas, R. L., Sheard, R. W., & Moyer, J. R. (1967). Comparison of conventional and automated procedures for N, P and K analysis of plant material using a single digestion. *Agronomy Journal, 59*, 240–243.

Weisenborn, D. P., Orr, P. H., Casper, H. H., & Tacke, B. K. (1994). Potato starch paste behaviour as related to some physical/chemical properties. *Journal Food Science, 59*, 644–648.

Williams, P. C., Kuzina, F. D., & Hlynka, I. (1970). A rapid colorimetric procedure for estimating the amylose content of starches and flours. *Cereal Chemistry, 47*, 411–420.

Zobel, H. F. (1988). Molecules to granules: A comprehensive starch review. *Starch, 40*, 44–50.