Nutritional and rheological characterization of spray dried sweetpotato powder ☆

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Abstract

Spray drying feasibility of sweetpotato puree is enhanced using alpha-amylase treatment to reduce puree viscosity and maltodextrin (MD) addition to facilitate drying. To better determine potential applications of powders produced with various levels of amylase and MD, nutrient composition and rheological properties of the hydrated spray dried sweetpotato powders were examined and compared with sweetpotato puree. Proximate composition, beta-carotene, vitamin C, and mineral analyses were performed. Steady shear rheology of reconstituted powder solutions was also evaluated at different temperatures and shear rates. Spray drying significantly reduced the β-carotene and ascorbic acid contents. Additionally, the *all-trans* form of beta-carotene was further transformed to the *cis*-isomers during dehydration. The viscosity of the reconstituted solutions was much lower than that of the puree at the same solid concentration. Rheologically, the reconstituted sweetpotato slurries behaved similarly to pregelatinized starch solutions. Thus, spray dried sweetpotato powders have a potential to enhance food systems as a thickener despite the need for increased nutrient retention.
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1. Introduction

Sweetpotatoes are highly nutritious vegetables; however, sweetpotato consumption is progressively declining especially in industrialized nations. Part of this decline may be attributed to the lack of sweetpotato based products for consumers beyond the baked roots. Conversely, the white potato has seen a great increase in production and a large portion of this increase is due to processed products such as chips, fries, and frozen products. Thus, one way to expand sweetpotato consumption is to develop appealing processed products or alternative uses for sweetpotato roots (Kays, 1985; Collins & Walter, 1992).

One approach intended to increase consumption is to convert sweetpotato puree into dried powder for use as a functional ingredient in food systems (Grabowski, Truong, & Daubert, 2006). Sweetpotatoes have been commercially dried into dehydrated flakes for many years. However, the resulting product has poor solubility, unattractive brown color, and limited applications. In general, fruit and vegetable powders have been described as value added ingredients in various food systems. Both freeze dried and drum dried fruit and vegetable powders deliver numerous functional and nutritional benefits. The characteristic flavors, colors, and nutrients as well as water binding properties of these powders make them an ideal addition to soups, sauces, marinades, baby foods, dips, extruded cereal products, fruit purees for confections, and fillings for frozen toaster snacks (Francis & Phelps, 2003; Pszczola, 2003).

Fruits and vegetable powders have been produced using spray drying (Bhandari & Howes, 1999; Abu-Jdayil, Banat, Jumah, Al-Asheh, & Hammad, 2004). However, this technique has not been developed for starchy vegetables

such as sweetpotatoes. Recently, Grabowski et al. (2006) demonstrated that sweetpotatoes can be spray dried into appealing powders. For successful spray drying of sweetpotato puree, alpha-amylase action was used as predrying treatment to reduce viscosity. Amylase reduces the viscosity of sweetpotato puree by hydrolyzing starch molecules to dextrins (Ice, Hamann, & Purcell, 1980; Szyperski, Hammann, & Walter, 1986). Additionally, maltodextrin (MD) was added to the puree in various concentrations to act as a drying aid. MD facilitates product recovery by raising the glass transition temperature of the product to reduce stickiness and partially encapsulating the material (Re, 1998; Bhandari & Howes, 1999). Both amylase addition and the use of MD are expected to affect the physicochemical characteristics of the powders.

Spray dried sweetpotato powders have a potential to be added to various food systems to provide a variety of functional benefits. To better determine the role of sweetpotato powder in different food applications, additional information about nutrient composition and functionality of these powders in reconstituted solutions is required. Sweetpotatoes are known as a rich source of carbohydrates, beta-carotene, ascorbic acid, and minerals. Unfortunately, many of these nutrients are degraded during thermal processing. In the production of dehydrated sweetpotato flakes, over 20% of the beta-carotene is lost while ascorbic acid (AA) losses have been reported as high as 50–70% (Arthur & McLemore, 1955; Chandler & Schwartz, 1988). Carbohydrate content also changes during processing, as the action of naturally available amylase at elevated temperatures transforms the sweetpotato starch to dextrins and sugars (Walter, Purcell, & Nelson, 1975). These chemical conversions also lead to altered functionality and changes in the flow behavior of reconstituted powder solutions.

Further testing is required to determine the effect of spray drying as well as amylase treatment and MD addition on nutrient composition and viscosity of reconstituted powder solutions. Significant retention of sweetpotato nutrients during processing is an ideal characteristic for a functional ingredient. Additionally, knowledge of the rheological properties of the reconstituted powders would be helpful in determination of potential product applications. Thus, the objective of this study was to characterize the nutrient composition and rheological properties of sweetpotato powders as affected by amylase hydrolysis for reduction of puree viscosity and addition of MD as a drying aid.

2. Materials and methods

2.1. Materials

Sweetpotato puree from the Beauregard cultivar, an orange-fleshed variety, was manufactured by Bright Harvest Sweet Potato Co. (Clarksville, AK). The puree with 18.2% solids was procured in 20 kg bag-in-box containers and stored frozen. Alpha-amylase from *Aspergillus oryzae* [Fungamyl 800 L (Novozymes, Bagsvaerd, Denmark)] was utilized for starch hydrolysis. This alphaamylase has optimum activity at an approximate pH of 5 and at temperatures between 50 and 60 °C. Using the chromogenic starch method with amylopectin azure as a substrate, the enzyme activity was measured at 22.9 amylase unit/mL (Grabowski et al., 2006). MD with a dextrose equivalent (DE) of 11 (MD 01960) was obtained from Cargill Inc. (Cedar Rapids, IA). Other chemicals used in experimentation were of analytical and HPLC grades.

2.2. Spray dried powder production

Sweetpotato puree was spray dried using a pilot scale dryer (Production Minor Spray Dryer, Niro Inc., Columbia, MD) equipped with a rotary atomizer set at 20,000 rpm and co-current air-product flow. Drying air was heated using natural gas combustion. Feed was moved into the dryer using a progressive cavity pump (Metering Pump, Moyno, Inc., Springfield, OH) and outlet temperature was maintained by adjusting the feed rate of product into the dryer. A cyclone was used to separate the powder from the air, and the powder was recovered at the bottom of the cyclone. Sweetpotato puree was spray dried with various predrying treatments using alpha-amylase hydrolysis and MD addition, and the resulting powders were compared to sweetpotato puree (Table 1).

Feed temperature (60 °C), solids content (18.2 g/100 g), inlet temperature (190 °C) and outlet temperature (100 °C) were held constant as optimized in previous study (Grabowski et al., 2006). A steam jacketed mixer was used to elevate the temperature of the puree. This mixer was also used to blend the puree and the alpha-amylase for the samples requiring enzyme treatment. The alpha-amylase (3.75 ml/kg puree, 85.9 APA amylase units/kg puree) was allowed to act for 30 min at 60 °C before the temperature of the puree was raised above 90 °C to deactivate the enzyme. For the combined amylase and MD treatment, the puree was treated with amylase, and then the enzyme was inactivated. MD was thoroughly mixed with the treated puree just prior to spray drying. In order to maintain the same amount of solids fed to the dryer, water was added to

Table 1
Experimental variables for sweetpotato spray drying

Treatment	Amylase (ml/kg puree)	Maltodextrin (g/100 g puree)
Puree	na*	na*
Control	0	0
Maltodextrin	0	10
Amylase	3.75	0
Amylase and Maltodextrin	3.75	10

*Not applicable.

the puree–MD mixture. Each treatment was spray dried in duplicate, and chemical and rheological analyses were performed on each duplicated sample and the sweetpotato puree. All samples were stored at −20 °C until analyzed.

2.3. Nutrient analysis

Moisture content of the spray dried powder was determined by Karl-Fischer titration method using a Karl Fisher 701 Titrino (Metrohm Ltd., Herisau, Switzerland). Methanol was used as the solvent, and hydranal composite 5 (Sigma-Aldrich, St. Louis, MO) was the reactant. The Karl Fisher unit was enclosed in a plexiglass dry box supplied with compressed air pumped in to maintain low humidity. The extraction time was set at 180 s to enable the sample (0.25 g powder) to fully dissolve. For puree samples, the moisture content was determined by drying a 5 g sample in an oven at 70 °C for 6 h and then at 105 °C overnight. All moisture measurements were performed in triplicate.

Protein, fat, and ash content determination of the sweetpotato puree and spray dried powders were performed by Silliker Laboratories (Stone Mountain, GA). Protein content was measured using Kjeldahl analysis using a protein factor of 6.25 according to AOAC Method 991.20.1. Fat content was determined using AOAC Method 933.05 and ash content by AOAC Method 925.51A (AOAC, 1995)

Fiber content was determined using the methods as outlined in AOAC Methods 991.43 and 985.29 (AOAC, 1995) using an assay kit (Megazyme International Ltd, Bray, Co. Wicklow, Ireland). Total dietary fiber was determined on duplicate samples of the spray dried powders, and the puree which was freeze dried before analysis. Samples were first cooked at ∼100 °C with heat-stable alpha-amylase to induce gelatinization, hydrolysis, and depolymerization of starch. Subsequently, samples were incubated at 60 °C with protease to solubilize and depolymerize proteins, and amyloglucosidase to hydrolyze starch fragments. Next, each sample was treated with ethanol to precipitate soluble fiber and remove depolymer-ized protein and glucose. The residue was then filtered; washed with 78% ethanol, 95% ethanol, and acetone; dried; and weighed. One of the duplicate samples was analyzed for protein, and the other used to determine ash content. The total dietary fiber was calculated as the weight of the dried residue less the weight of the protein and ash.

For sugar analysis, powder sample (100 mg) was mixed with 5.0 ml of 95% ethanol in a centrifuge tube. The tube was then incubated at 80–85 °C for 10 min, mixed on a vortex stirrer, and another 5 ml of ethanol was added to the tube. The tube was then centrifuged for 10 min at 3000 rpm, and the supernatant was collected. The remaining pellet was resuspended in 10 ml of ethanol to repeat the extraction. The sugar extracts were combined in a 25 ml volumetric flask and filled to volume with ethanol. A 5 ml aliquot of this solution was transferred to a small beaker

and the ethanol was allowed to evaporate completely overnight. In preparation for High Performance Liquid Chromatography (HPLC), 1 ml of the internal standard (cellobiose) solution was added to the beaker to dissolve the residue. Fifty microliter of this solution was diluted to 2 ml with water in small test tube. Sugar analyses were conducted using a Dionex BioLC AD 50 HPLC system (Sunnyvale, CA). Ten microliter samples were injected and eluted through a Carbo PAC PA-1 column (250 × 4.6 mm id) (Dionex Corporation, Sunnyvale, CA) at 30 °C. The mobile phase consisted of 200 mM sodium hydroxide at an isocratic flow rate of 1.0 ml/min. Peaks were detected by a Dionex PAD (pulse amperometric detector) and identified based on retention time. To determine sugar content, the peak heights of sucrose, glucose, fructose, and maltose were compared to that of the standard solution of cellobiose (Pattee, Isleib, Giesbrecht, & McFeeters, 2000).

Starch content was determined using an assay kit (Megazyme International Ltd, Bray, Co. Wicklow, Ireland) according to AOAC Method 996.11 (AOAC, 1995). Powder samples were first washed with ethanol to remove the sugars as described above. The remaining pellet was then treated with 2 ml of dimethyl sulfoxide at 100 °C to account for resistant starch. The samples were cooked with thermostable alpha amylase to partially hydrolyze and solubilize the starch. Subsequently, the samples were treated with amyloglucosidase for 30 min at 50 °C to hydrolyze the starch dextrins to glucose. The samples were then transferred to 100 ml volumetric flasks and filled to volume with distilled water. An aliquot of this solution was centrifuged at 3000 rpm for 10 min, and the supernatant was mixed with a glucose determination reagent and incubated at 50 °C for 20 min. The absorbance of the solution at 510 nm was read on a Cary 300 Bio spectro-photometer (Varian Inc., Research Triangle Park, NC) against a reagent blank. Starch content was calculated based on the absorbance of the sample with reference to a glucose standard.

Beta-carotene was extracted from the puree and powder and analyzed using an HPLC system. For extraction, 5 g of sample was mixed with approximately 2 g of calcium carbonate, 1 g of diatomaceous earth, and 25 ml of methanol. Fifty milliliter of hexanes–acetone (1:1) mixture were added and stirred. The mixture was filtered under vacuum through a funnel with a fritted disk. The residue in the funnel was washed with 25 ml of methanol and 50 ml of the hexane–acetone mixture for two more times or until the filter cake was colorless. The combined extract was transferred to a 250 ml separatory funnel and washed with water. A few drops of saturated sodium chloride solution were added to the funnel to facilitate sharp delineation of the phases. The aqueous phase was released and the upper layer was transferred to a 50 ml volumetric flask and filled to volume with hexane (Chandler & Schwartz, 1988). All extractions were performed in a laboratory with UV-filtered light to prevent light degradation of carotene, and the extracts were stored in dark vials at −20 °C. HPLC

analysis of the carotene content was performed according to the method of Yeum et al. (1996). The HPLC system consisted of a series 410 LC pump (Perkin Elmer, Norwalk, CT), a Waters 717 plus autosampler (Millipore, Milford, MA), a C30 carotenoid column (3 μm, 150 × 4.6 mm, YMC, Wilmington, NC), a column temperature controller (model 7950; column heater/chiller, Jones Chromatography, Lakewood, CO), a Waters 994 photodiode array detector, and a Waters 840 digital 350 data station. The mobile phase consisted of methanol:methyl-tert-butyl and ether:water. The eluent flow rate was 1 ml/min at 16 °C. Peak identification was based on the retention time of respective carotene isomers. Carotenes were quantified by determining peak areas in the chromatograms as compared to known standards.

Vitamin C activity was quantified by determining the amount of AA dehydroascorbic acid (DHAA) in the sample by HPLC. Samples (5 g) were mixed with 30 ml of a 5% metaphosphoric acid solution, centrifuged and the extract was analyzed using an HPLC system (ThermoQuest San Jose, CA) consisting of a P2000 binary pump, AS 3000 autosampler, and SCM 1000 degasser. Samples were placed in the sample tray set at a temperature of 6 °C with a light proof covering. Samples (20 μl) were injected onto a 3 μm reverse phase column (4.6 × 150 mm) (Bondapack-NH$_2$ Z-module cartridge, Waters Associates, Milford, MA) and were separated at 35 °C under isocratic conditions with an eluent flow rate of 1.2 ml/min. The mobile phase consisted of aqueous 0.005 M KH$_2$PO$_4$ and acetonitrile (30:70 v/v). Peaks were monitored at 450 nm by a UV 6000 LP Diode Array Detector. Standard solutions with concentrations from 0.5 to 10 mg/ml were used for the calculations. The R^2 of the standard curve was greater than 0.99 with the intercept forced through zero. ThermoQuest Chromatography Data Acquisition Software version 4.1 was used to collect and process the data.

Phosphorous, calcium, magnesium, potassium, iron, and sodium content was analyzed by the Analytical Services Lab, Department of Soil Science at North Carolina State University. Samples underwent dry combustion and dissolution of the residue in acid. The mineral digest was then analyzed on a Perkin Elmer Ion Coupled Plasma (ICP) Spectrometer (Perkin Elmer Corp, Norwalk, CT). Duplicate analysis was performed on each treatment replication.

2.4. Rheological testing

Powder samples were reconstituted to the same solids content as the puree (18.2%). Five grams of powder were mixed with 27.5 g of water in a 50 ml test tube using a vortex mixer set on the highest speed for 2 min. Samples were allowed to equilibrate for approximately 1 h at room temperature before rheological measurements were taken. Viscosity of the puree was determined using a Stress Tech Rheometer (Reo Logica Instruments, Lund, Sweden) with a serrated bob and cup geometry. The sample was covered with a thin layer of oil and a cover to minimize moisture

loss. Samples were presheared for 60 s at 25 s^{-1} and allowed to rest for 25 s before testing began. Shear rate sweeps were performed on the samples at 25, 75, and 95 °C with shear rate ramped up and down from 1 to 250 s^{-1}. Samples were allowed to equilibrate for 60 s at the set temperature before the shear rate sweeps were performed. Two cycles of the shear rate ramp were performed at 75 °C to look for different time dependent phenomena. For temperature ramps, puree and reconstituted solutions were sheared at a constant rate of 10 s^{-1} while the temperatures were increased from 25 to 75 °C, continued from 75 to 95 °C, and then cooled to 25 °C at a rate of 1.5 °C/min.

Flow behavior was described by the Herschel–Bulkley:

$$\sigma = \sigma_0 + K\dot{\gamma}^n, \tag{1}$$

where σ, shear stress; $\dot{\gamma}$, shear rate; σ_0, yield stress; K, consistency coefficient; and n, flow behavior index (Steffe, 1996).

2.5. Statistical analysis

Nutrient composition data was analyzed using the Statistical Analysis System (SAS Institute v.8.0, Cary, NC). Analysis of variance and means separation were calculated by the general linear model procedure. Differences between treatments ($p < 0.05$) were evaluated by the least squares mean procedure with a Tukey adjustment.

3. Results and discussion

3.1. Nutrient composition

3.1.1. Proximate analysis

Results of proximate analysis on sweetpotato puree and spray dried powders are found in Table 2. All powders were dried to an acceptable level below 5 g water/100 g and no differences ($p > 0.05$) in moisture content existed between spray drying treatments.

Starch content was higher in the spray dried samples containing MD (Table 2). The higher starch value in the MD samples can be attributed to the added MD, a starch hydrolyzate. Typically, sweetpotato roots have approximately 30–70 g starch/100 g dry weight basis (db) (Woolfe, 1992). However, when sweetpotatoes are heated, the natural amylases become active and degrade the starch molecules into dextrins and sugars until the enzymes are inactivated. Walter and Purcell (1976) reported a decrease in starch concentration and increase in maltose and dextrins in dehydrated sweetpotato flakes as the length of time the puree was exposed to enzyme activity prior to drying was increased. Truong, Biermann, and Marlett (1986) reported a 4–14% decrease in starch content when sweetpotatoes were cooked for 30 min. Arthur and McLemore (1955) reported starch values of 33–43 g/100 g raw roots which decreased to between 2 and 10 g/100 g (db) dehydrated flakes. Thus, the starch content was expected to be lower in spray dried powder pretreated with amylase for

Table 2
Proximate analysis of sweetpotato puree and spray dried powder

Treatment	Moisture	Starch	Total sugar	Total dietary fiber	Protein	Lipid	Ash
	(g/100 g)	g/100 g dry matter					
Puree	81.7[a]	33.1[b]	31.9[b,c]	11.3[a]	6.1[a]	2.3[a]	3.8[a]
Control	3.7[b]	32.0[b]	40.1[a,b]	7.0[a,b]	4.8[a]	0.6[b]	4.3[a]
Maltodextrin	2.6[b]	58.8[a]	28.4[c]	3.5[b]	3.3[b]	0.4[b]	2.4[b]
Amylase	3.1[b]	26.9[b]	42.5[a]	7.8[a,b]	5.0[a]	0.5[b]	3.9[a]
Amylase and Maltodextrin	2.5[b]	46.9[a]	36.2[a,b]	5.7[a,b]	3.1[b]	0.6[b]	2.6[b]
CV*	4.7	5.8	4.3	16.4	11.0	15.2	10.1

Different letters within columns indicate a significant difference at $p < 0.05$.
*Coefficient of variation.

viscosity reduction. The amylase treatment does indeed have the lowest starch content, but this treatment does not significantly reduce the starch compared to the control powder. Total sugar content of the spray dried powders was similar to the values reported for dehydrated flakes (32–45 g/100 g db) (Arthur & McLemore, 1955). Each powder sample had a higher sugar content compared to the puree except for the MD-treated sample where the total sugar content was diluted by the addition of MD.

The addition of MD increased the amount of non-sweetpotato solids in the powder samples which in turn lowered the fiber, protein, and ash content of the MD-added powders. The control and amylase-treated samples were not significantly different than the puree for these components. Raw sweetpotatoes contain approximately 2–10 g fiber/100 g (db) (Purcell, Walter, & Wilson, 1989; Woolfe, 1992; Huang, Tanudjaja, & Lum, 1999). The fiber content of the powder samples ranges from 3.5 to 7.8 g/100 g and was lower, but not significantly different, than the fiber content of the puree except for the aforementioned added MD differences.

Protein values of the spray dried powders were also lower than that of the puree. The crude protein contents of sweetpotato roots has been reported between 1.2 and 10 g/100 g including a considerable amount of the biologically active amino acid, lysine. However, heat processing treatments such as canning and flaking have been related to a reduction in protein and amino acid content (Walter, Collins, & Purcell, 1984). Thus, the lower protein content of the powders could be attributed to the destruction of lysine through interaction with the reducing groups of carbohydrates at high temperatures. The Maillard reaction is a complex set of reactions initiated by reaction of an amine group of a protein and a carbonyl group of a reducing sugar at elevated temperatures. During these reactions, lysine becomes biologically unavailable and also may further degrade by participating in the Strecker degradation reaction (Damodaran, 1996).

The lipid content of the powders was significantly lower than that of the puree. Lipid oxidation of drum dried sweetpotato flakes has been a common problem resulting in reduction of lipid content (Walter & Purcell, 1974).

Similarly, greatly increasing the surface area through spray drying exposes more area in sweetpotato powders for oxidation and degradation to take place, thus reducing the lipid concentration.

3.1.2. Vitamin C and minerals

Vitamin C activity of the puree was significantly reduced by spray drying (Table 3). Again, the addition of MD decreased the overall sweetpotato solids and thus the amount of vitamin C in those powders. Both AA and DHAA, the oxidized form of AA, contribute to vitamin C activity. However, if DHAA is further hydrolyzed to 2,3-diketogulonic acid, then vitamin C activity is lost. The rate of DHAA hydrolysis markedly increases with increasing temperature (Gregory, 1996). Raw sweetpotatoes contain between 17 and 35 mg/100 g of vitamin C on a fresh weight basis (fwb) (Bradbury & Singh, 1986; Purcell et al., 1989; Woolfe, 1992). However, these levels are significantly reduced by thermal processing. Bradbury and Singh (1986) reported baking sweetpotatoes for 30 min reduced AA and DHA by 45–55%. Boiling sweetpotatoes for less than 20 min decreased levels of AA and initially increased DHA. After 20 min, DHA concentration also began to decrease. A 50–70% decrease in vitamin C was reported for sweetpotato flakes drum dried at high temperatures. Sweetpotato flakes were reported to have AA levels between 55 and 94 mg/100 g (db) with initial root levels of 103–105 mg/100 g (db) (Arthur & McLemore, 1955). Bradbury and Singh (1986) reported levels of 48.6 and 23.8 mg/100 g (db) for AA and DHAA in a representative cultivar from the South Pacific and levels of 10.8 and 12.6 mg/100 g (db) after cooking. The vitamin C values for the spray dried powders and the puree in the current study are much lower than these previously reported values. In addition to thermal treatments, some oxidation and hydrolysis over storage time could account for these low values.

Raw sweetpotatoes contain 10–64 mg phosphorous (P); 110–403 mg potassium (K); 20–41 mg calcium (Ca); 10–22 mg magnesium (Mg); 0.59–0.86 mg iron (Fe); and 13–30 mg sodium (Na) per 100 g on a fresh weight basis (Picha, 1985; Woolfe, 1992). On dry weight basis, the levels of these minerals are comparable with the mineral contents

Table 3
Vitamin C and mineral content of sweetpotato puree and spray dried powder (mg/100 g) (db)

Treatment	Vitamin C activity*	P	Ca	Mg	K	Fe	Na
Puree	5.8[a]	149[a]	110[a]	72.4[a]	1343[a]	2.8[c]	74.5[c]
Control	1.4[b]	202[a]	151[a]	99[a]	1822[a]	4.8[b]	122[b,c]
Maltodextrin	0.9[b,c]	133.5[a]	82[a]	61.5[a]	1058[a]	2.64[c]	73.0[c]
Amylase	1.3[b,c]	185[a]	124[a]	87.5[a]	1621[a]	2.9[c]	177[b]
Amylase and Maltodextrin	0.2[c]	123[a]	82[a]	51[a]	980[a]	1.8[c]	143[b]
CV**	13.5	12.8	15.8	19.4	9.4	12.0	12.2
Dietary reference intake***	65–90	700–1250	1000–1300	360–420	4.7 g	8–18	1.3–1.5 g

Different letters within columns indicate a significant difference at $p < 0.05$.
*Total vitamin C activity as the sum of ascorbic acid and dehydroascorbic acid.
**Coefficient of variation.
***DRI values are in mg/day unless otherwise noted.

Table 4
Cis/trans beta-carotene isomers in sweetpotato puree and spray dried powders (mg/100 g) (db)

Treatment	Trans	9 Cis	13 Cis	Total beta-carotene equivalent	% Cis isomers
Puree	35.4[a]	0.28[a]	4.18[a]	38.0[a]	11.2
Control	10.5[b]	0.32[a]	0.68[b,c]	11.1[b]	8.7
Maltodextrin	0.3[c]	0.12[a]	0.11[c]	0.43[c]	42.1
Amylase	13.2[b]	0.35[a]	1.11[b]	14.0[b]	10.0
Amylase and Maltodextrin	0.81[c]	0.04[a]	0.12[c]	0.90[c]	16.4
CV*	16.5	39.2	16.7	15.9	

Different letters within columns indicate a significant difference $p < 0.05$.
*Coefficient of variation.

of the sweetpotato puree and spray dried powders presented in Table 3. Levels of the Dietary Reference Intakes for adults are also listed in Table 3. One hundred grams of sweetpotato powder provides between 14% and 28% of the DRI for magnesium and 20–39% for potassium. Levels of the other minerals fall below 10% of the DRI for these minerals.

3.1.3. Beta-carotene

Values for beta-carotene content of the sweetpotato puree and spray dried powders are shown in Table 4. Spray drying sweetpotato puree significantly decreased total amount of beta-carotene and caused isomerization of the molecule. Carotenoids are easily isomerized by heat, acid, or light. In general, carotenoids exist in an *all-trans* configuration. When exposed to heat, the molecule may transform to a *cis* configuration typically at the 9, 13, and 15 carbon positions. Also, dehydration processes may contribute to oxidative degradation due to exposure to oxygen and an increased surface to mass ratio (von Elbe & Schwartz, 1996).

Raw sweetpotatoes contain between 0.5 and 45 mg/100 g (db) of beta-carotene (Purcell & Walter, 1968; Kays, 1992; Lessin, Catignani, & Schwartz, 1997). The original levels of beta-carotene can be reduced during the thermal processing of sweetpotatoes such as pureeing and dehydration (Table 4). In previous works, canning and pureeing actually showed an increase in total beta-carotene content

but this increase was attributed to enhanced extraction efficiency (Chandler & Schwartz, 1988; Lessin et al., 1997). Drum drying, however, led to a loss in total beta-carotene content (Arthur & McLemore, 1955).

Depending on the severity of the heat treatment, the *all-trans* beta-carotene is more prone to isomerization than to degradation (Chandler & Schwartz, 1988). As shown in Table 4, the puree in this study had 11.2% *cis* isomers while isomers in the spray dried powders ranged from 8.7% to 42%. Chandler and Schwartz (1988) reported a very slight increase in *cis* isomers in the pureed product. However, drum drying showed a 20.5% loss in total beta-carotene and a 24% increase in *cis* isomers. Puree had total beta-carotene content of 48.6 mg/100 g (db) with 5.2% isomers while the drum dried flakes had total beta-carotene content of 35.0 mg/100 g (db) with 28.9% cis isomers. Most of these isomers existed at the 13 carbon position with only trace amounts at the 9 carbon position. Similarly, the results of the current study showed the greatest amount of isomerization at the 13 carbon position (Table 4).

Samples with added MD had the lowest amount of beta-carotene content as MD makes up a significant percent of the total solids content of the powder. These samples surprisingly also had an increased amount of isomerization and loss of beta-carotene as seen in Table 4 and the representative chromatograms (Fig. 1). MD is often used as an encapsulating agent to protect sensitive ingredients from the environment by forming a coating around the
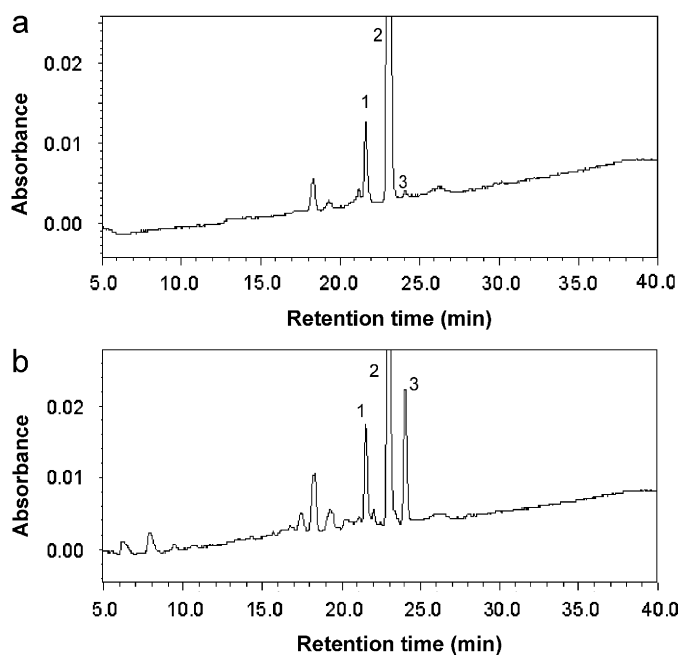
Fig. 1. Representative chromatograms of the separation of beta-carotene isomers. (peak 1, 13-*cis*; peak 2, all-*trans*; peak 3, 9-*cis*). (a) sweetpotato puree (b) sweetpotato powder spray dried with maltodextrin.

material. Previous researchers demonstrated the use of MD in reducing oxidative degradation of carotenes during storage depending on the concentration of MD, the level of hydrolysis of the MD, and drying technique (Wagner & Wathesen, 1995; Desobry, Netto, & Labuza, 1997). Therefore, the MD-treated samples were expected to retain a higher percentage of beta-carotene. Despite the protective effects of MD, however, Desobry et al. (1997) reported an 11% loss in beta-carotene during the spray drying of pure beta-carotene with MD as a drying aid. Further, beta-carotene could have been oxidized during the storage time between powder production and testing. Wagner and Wathesen (1995) reported that MDs with a higher DE, or degree of hydrolysis gave better oxidative protection than lower DE MDs. The MD with DE = 11 used in this study may not have sufficiently protected the beta-carotene from oxidation during the storage time prior to testing.

Beta-carotene pigments impart cream, yellow, orange, and deep orange color in sweetpotato roots (Woolfe, 1992). Previous researchers have found a correlation between Hunter color values and the beta-carotene content in sweetpotatoes. Simonne, Kays, Koehler, and Eitenmiller (1993) reported positive linear relationships between *a* and *b* values and beta-carotene while a negative linear relationship between beta-carotene and *L* value and hue angle was observed. In a previous study on spray dried sweetpotato powders (Grabowski et al., 2006), similar results were noted. As beta-carotene decreased with spray drying treatment, L^* values and hue angle increased while a^* and b^* values decreased.

Despite the significant decrease in total beta-carotene content, the spray dried sweetpotato powders may still

contribute to vitamin A in the human diet. The Recommended Dietary Allowance (RDA) for vitamin A is 0.6–0.9 mg/day which translates to approximately 7–10.8 mg of beta-carotene (Food & Nutrition Information Board, 2004). Consuming 100 g of the control and amylase-treated powders could significantly contribute to vitamin A activity.

3.2. Rheological properties

Shear rate ramps were performed at 25, 75, and 95 °C to investigate shear and temperature effects on the apparent viscosity of four spray dried powders reconstituted to the same solid concentration (18.2 g/100 g) as the original puree. Fig. 2 shows a representative rheogram of the puree and the reconstituted powder solutions at 25 °C. Table 5 summarizes model parameters and apparent viscosities at 10, 50, and 100 s^{-1}. The viscosity of all samples decreased with increasing temperature. At all temperatures, the viscosity of the puree was an order of magnitude greater than all of the powder solutions. The solutions of the control and amylase-treated samples had similar viscosities which were both greater than the samples containing MD (Fig. 2).

The flow behavior of the puree was best fit to Herschel–Bulkley model showing pseudoplastic behavior with a yield stress while most of the powders did not have a yield stress and fit the power law model. For the puree, consistency coefficients (K) ranged from 37 to 61 Pa s^n and flow behavior indexes (n) were between 0.15 and 0.36. These K values of the Herschel–Bulkley model are slightly higher than those reported by other researchers for sweetpotato puree while the n values are in the same range. Kyereme, Hale, and Farkas (1999) reported consistency coefficients between 2.8 and 21.5 Pa s^n and flow behavior indexes between 0.20 and 0.33 for sweet-potato puree measured at temperatures between 10 and 90 °C. Rao, Hamann, and Humphries (1975) reported
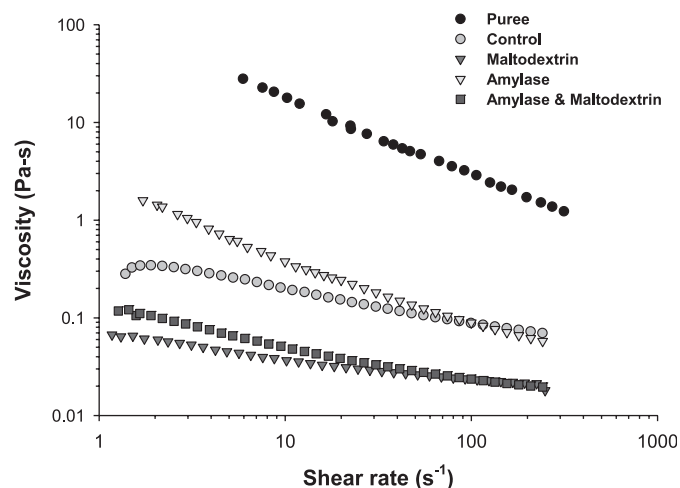

Fig. 2. Viscosity of sweetpotato puree and reconstituted powders with 18.2% solids at 25 °C sheared from 1 to 250 s^{-1}.

Table 5
Herschel–Bulkley (HB) parameters and viscosities of 18.2% solids sweetpotato puree and reconstituted spray dried powder solutions at 25, 75, and 95 °C and at shear rates between 1 and 250 s^{-1}

Sample	Temperature (°C)	σ_0 (Pa)	K (Pa s^n)	n	R^2	η_{10} (Pa s)	η_{50} (Pa s)	η_{100} (Pa s)
Puree	25	93.5 ± 2.1	36.9 ± 10.2	0.36 ± 0.3	0.98	17.81 ± 1.88	4.92 ± 0.22	2.81 ± 0.34
	75	30.0 ± 14.1	45.6 ± 2.6	0.31 ± 0.02	0.99	11.40 ± 0.87	3.69 ± 0.37	2.10 ± 0.23
	95	32.5 ± 17.6	61.3 ± 3.3	0.14 ± 0.01	0.85	6.00 ± 0.89	1.30 ± 0.20	0.76 ± 0.13
Control	25	–	0.4 ± 0.1	0.65 ± 0.03	0.99	0.19 ± 0.06	0.10 ± 0.03	0.08 ± 0.02
	75	–	0.6 ± 0.3	0.21 ± 0.06	0.99	0.10 ± 0.03	0.05 ± 0.01	0.04 ± 0.01
	95	–	0.2 ± 0.1	0.63 ± 0.01	0.99	0.08 ± 0.03	0.05 ± 0.02	0.04 ± 0.01
Maltodextrin	25	–	0.6 ± 0.4	0.80 ± 0.13	0.99	0.04 ± 0.01	0.03 ± 0.01	0.02 ± 0.00
	75	–	0.6 ± 0.4	0.72 ± 0.16	0.99	0.02 ± 0.01	0.01 ± 0.00	0.01 ± 0.00
	95	–	0.6 ± 0.4	0.72 ± 0.18	0.99	0.03 ± 0.02	0.02 ± 0.01	0.01 ± 0.00
Amylase	25	–	1.1 ± 1.0	0.35 ± 0.04	0.97	0.31 ± 0.18	0.13 ± 0.08	0.09 ± 0.05
	75	–	0.8 ± 0.5	0.34 ± 0.01	0.97	0.21 ± 0.16	0.08 ± 0.06	0.05 ± 0.03
	95	–	0.7 ± 0.4	0.39 ± 0.03	0.96	0.19 ± 0.17	0.07 ± 0.05	0.04 ± 0.03
Amylase and Maltodextrin	25	–	0.6 ± 0.4	0.65 ± 0.02	0.99	0.05 ± 0.01	0.03 ± 0.00	0.02 ± 0.00
	75	–	0.5 ± 0.3	0.45 ± 0.01	0.98	0.06 ± 0.01	0.02 ± 0.00	0.02 ± 0.00
	95	–	0.6 ± 0.3	0.55 ± 0.07	0.98	0.06 ± 0.01	0.02 ± 0.00	0.02 ± 0.00

similar consistency coefficient values between 1.79 and 24.8 Pa s^n while flow behavior index values were slightly higher (0.33–0.56) for seven different cultivars. The yield stress for the puree in this study was similar to a range of 23–66.3 Pa reported by Rao et al. (1975), but it was much higher than the yield stress of 10 Pa reported by Kyereme et al. (1999). The powder solutions had much lower consistency coefficient values (0.2–1.1 Pa s^n) and higher flow behavior index values (0.21–0.81) than the puree. Solutions with MD had the lowest consistency coefficients and higher, nearing Newtonian ($n = 1$), flow behavior indexes.

The solids concentration in the puree and reconstituted solutions was the same (18.2%); however, the puree viscosity was much greater than the powder viscosity at all temperatures. Abu-Jdayil et al. (2004) reported similar results for tomato paste and spray dried tomato powder solutions. In the tomato products, viscosity differences were attributed to changes to pectins and other long chain carbohydrate polymers found in the tomato paste during spray drying. These polymers are degraded by the heat of spray drying resulting in smaller molecules which affect the colloidal properties of the solution. Additionally, large differences in particle size between the dried tomato powder and tomato paste, which has suspended particles in colloidal serum, accounted for differences in yield stress and viscosity. Similarly for sweetpotatoes, starch molecules are degraded during processing, losing the ability to swell and increase viscosity.

The powder samples containing MD were the least viscous. Preliminary testing showed that a 10 g MD/100 g solution had a viscosity of less than 5 mPa s while the viscosity of a 20 g/100 g solution was less than 6 mPa s. In the sweetpotato powders, MD comprised less than 2 g/100 g of the total solid content, and thus MD did not

contribute to increased viscosity. At low concentrations, MD is known for having superior cold water solubility (BeMiller & Whistler, 1996). In the previous study on spray dried sweetpotato puree (Grabowski et al., 2006), the water solubility index of the powders increased as the amount of MD added increased. With more of the spray dried powder solubilized into solution, there was less sweetpotato solids to create resistance to flow in the mixture. Additionally, as the MD encapsulated the sweetpotato material, it could be that there were interactions between the MD and the other polysaccharides present in the powders. These interactions did not allow these polysaccharides to fully extend in solution. Since longer molecules have a larger hydrodynamic volume which increases solution viscosity, the MD–polysaccharide interaction facilitated a decreased solution viscosity compared to the other samples.

The flow behavior of the spray dried sweetpotato powder solutions was similar to that of pregelatinized starch solutions. All the reconstituted solutions were shear-thinning and displayed slight thixotropy (Fig. 3). The hysteresis loops at 75 °C were similar for both shear ramp cycles. Additionally, most sweetpotato powder and pregelatinized starch solutions are best described by the power law model (Doublier, Colonna, & Mercier, 1986; Anastasiades, Thanou, Loulis, Stapatoris, & Karapantsios, 2002). For 8 g pregelatinized wheat starch per 100 g solutions, at a temperature of 60 °C and shear rates between 0 and 662 s^{-1}, apparent viscosity ranged from 0.99 to 0.02 Pa s (Doublier et al., 1986). For modified maize starch pastes with concentrations between 3.5 and 4.5 g solids/100 g, apparent viscosity ranged from 2 to 0.002 Pa s over shear rate range of 1–200 s^{-1} at 40 °C (Anastasiades et al., 2002). The viscosity of the sweetpotato powders at 18.2 g solids/100 g solution was in the same range but somewhat lower (0.3–0.02 Pa s). Thus, sweetpotato powders behave similarly
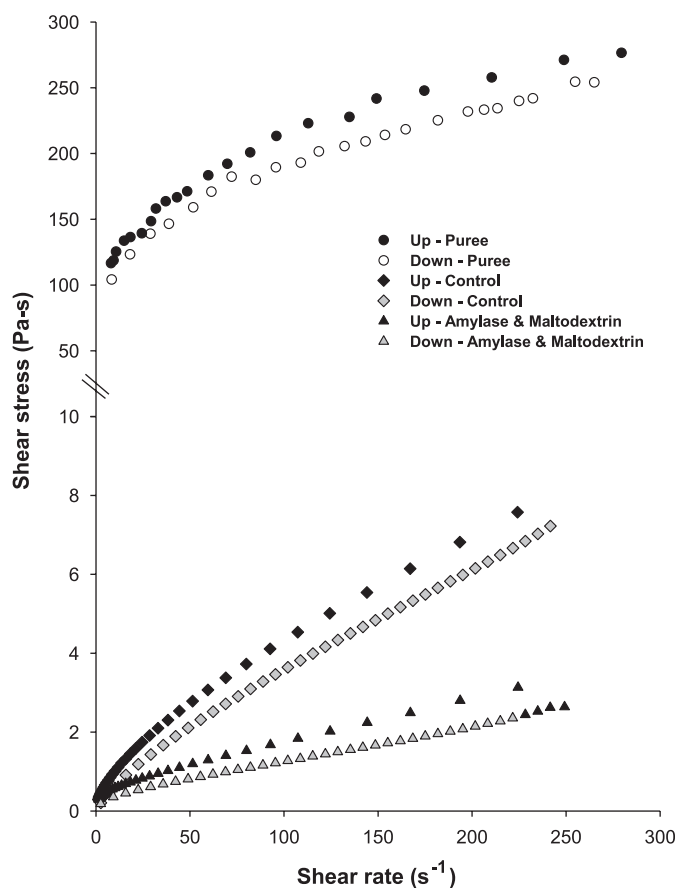
Fig. 3. Shear rate ramps from 1 to $250 \, \mathrm{s}^{-1}$ of sweetpotato puree and powders at 75 °C. Differences between the up and down ramps indicate time-dependent behavior.

Fig. 4. Viscosity of spray dried powders heated and cooled from 25 to 95 °C at a constant shear rate ($10 \, \mathrm{s}^{-1}$).

to pregelatinized starches in solutions; however, a much higher concentration of sweetpotato powder is required.

Similar to spray dried sweetpotato powders, the pseudoplastic behavior of pregelatinized starch solutions was also demonstrated by a flow behavior index of less than 1. The sweetpotato powders had flow behavior indexes between 0.2 and 0.8. For maize starch slurries with concentrations between 3.5 and 4.5 g starch/100 g solution, the flow behavior index varied from 0.34 to 0.44 (Anastasiades et al., 2002). Flow behavior index values for 5–9.5 g modified wheat starch per 100 g solution were slightly higher between 0.6 and 0.7 at 60 °C (Doublier et al., 1986).

Subjecting the puree and spray dried powders to a temperature ramp under a shear rate of $10 \, \mathrm{s}^{-1}$ produced little variation in apparent viscosity (Fig. 4). For example, the viscosity of control sample was reduced from 0.34 to 0.133 Pa s as temperature was ramped from 25 to 95 °C. Sample viscosity was higher during cooling from 95 to 25 °C. In a study of corn starches modified by acid hydrolysis, Wang, Truong, and Wang (2003) reported that the starch solution transformed from a sol to a weak gel during cooling. While the puree, amylase, and MD samples behave similarly to the control sample during the temperature ramp, the sample with amylase and MD
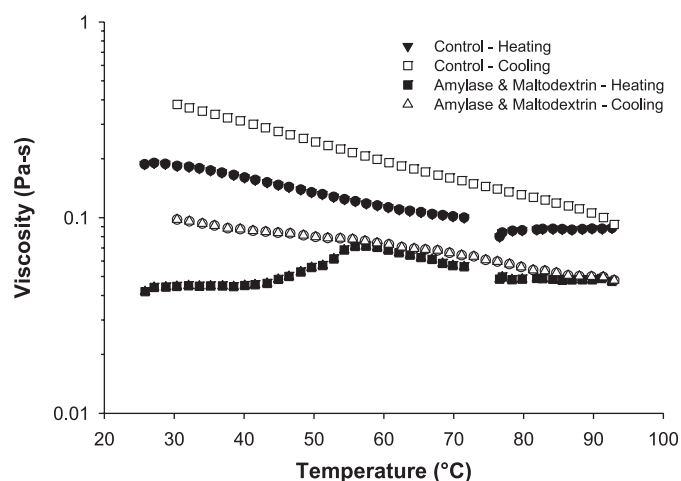
treatments displayed different behavior that requires further investigation. As the temperature was increased from 25 to 55 °C, the apparent viscosity increased from 0.042 to 0.070 Pa s. The viscosity then decreased until the temperature reached 70 °C and remained fairly constant (0.048 Pa s) until 95 °C. Reducing the temperature from 95 to 25 °C for the amylase and MD sample increased the viscosity from 0.048 to 0.098 Pa s similar to the other powder samples. During heating, the interaction between MD and polysaccharides present in sweetpotatoes may be slightly disrupted thus releasing these long chain molecules into solution and slightly increasing viscosity. Upon further heating, the solution viscosity decreases as elevated temperature weakens molecular interactions.

4. Conclusions

Sweetpotato nutrients such as beta-carotene and AA were significantly reduced during the spray drying of sweetpotato puree. In addition to thermal degradation of components, the addition of MD as a drying aid diluted the amount of nutrients in the resulting powder. A decreased level of sweetpotato solids as well as the interaction between MD and sweetpotato polysaccharides contributed to decreased viscosity of the reconstituted puree. Overall, the flow behavior of sweetpotato powders in reconstituted solutions was different than sweetpotato puree at the same solids concentration due to molecular changes during spray drying. Sweetpotato powders in solution behaved similarly to pregelatinized starch solutions but required higher concentrations for the same effects.

Sweetpotato powder may have the potential to act as a functional ingredient for enhancing natural color and flavor and acting as a thickening ingredient like pregelatinized starches in food systems. However, the results indicate that the nutrient composition of spray dried sweetpotato powders would have to be improved to make the powders more attractive to product developers and

consumers. Thus, the optimal level of MD required to balance cost effective drying with powder quality will have to be determined. Additionally, further study is required on how to better retain beta-carotene and AA during drying and subsequent storage.

Acknowledgments

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