

Anthocyanin Content, Antioxidant Activity, and Selected Physical Properties of Flowable Purple-Fleshed Sweetpotato Purees

L.E. STEED AND V.-D. TRUONG

ABSTRACT: With high levels of polyphenolic compounds, purple-fleshed sweetpotatoes (PFSP) have been utilized as a healthy food commodity and source of natural food colorants in Asia. In the U.S. sweetpotato industry, there are growing interests in exploring these market opportunities for PFSP. A locally grown PFSP cultivar was analyzed for antioxidant properties. The total phenolic content ranged from 313.6 to 1483.7 mg chlorogenic acid equivalent/100 g fresh weight (fw), and anthocyanin contents were between 51.5 and 174.7 mg anthocyanins/100 g fw. The DPPH radical scavenging activities and were 47.0 to 87.4 μmol trolox equivalent (TE)/g fw, and the oxygen radical absorbance capacity (ORAC) values were between 26.4 and 78.2 μmol TE/g fw. Unlike orange-fleshed sweetpotatoes (OFSP), the steamed roots of PFSP formed a thick paste, which required a process modification to produce flowable purees. Rheological testing indicated that adjusting the dry matter of PFSP to 18%–21% produced purees with flow properties similar to the OFSP purees. The PFSP purees had polyphenolic content and antioxidant capacity within ranges reported for various purple-colored fruits and vegetables.

Keywords: anthocyanins, antioxidant capacity, purees, purple-fleshed sweetpotatoes, rheological modeling, total phenolics

Introduction

Purple-fleshed sweetpotatoes (PFSP) have intense purple color in the storage roots due to the accumulation of anthocyanins (Philpott and others 2003; Terahara and others 2004). Sweetpotato anthocyanins exist in mono- or diacylated forms of cyanidin and peonidin, which contribute to the high antioxidant activity of PFSP as compared to sweetpotatoes of white, yellow, and orange flesh colors (Teow and others 2007). Recent research on the nutraceutical properties of PFSP indicated that the extracted anthocyanins exhibited strong radical scavenging activity and antimutagenic activity, and significantly reduced high blood pressure and carbon tetrachloride-induced liver injury in rats (Suda and others 1997; Yoshimoto and others 1999; Oki and others 2002). Other physiological functions of anthocyanins include anti-inflammatory, antimicrobial, and ultraviolet protection effects (Suda and others 2003).

In the past few years, sweetpotato cultivars with deep purple flesh were developed in Japan, Korea, New Zealand, and other countries to meet a growing demand in the health food markets (Lee and others 2000; Yamakawa and Yoshimoto 2002; Philpott and others 2003). Prominent examples are the Yamagawa-murasaki and Ayamurasaki cultivars in Japan, which are utilized in a variety of processed commercial products, including natural food colorants, juices, bread, noodles, jams, confectionary, and fermented beverages (Yamakawa and Yoshimoto 2002; Suda and others 2003). In

the United States, orange-flesh sweetpotatoes (OFSP) are predominantly consumed (Collins and Walter 1992). Utilizing new cultivars that have the nutritious benefits of OFSP and also contain additional functional pigments, including flavones, phenolic acids, and anthocyanins, is 1 way to expand the market opportunities for the sweetpotato industry (Suda and others 2003).

Despite the well-published health benefits of sweetpotatoes, global consumption has been in a state of decline for the past decades (Kays 1985). A main strategy to combat this declining trend is to expand the selection of processed products available to consumers, including dehydrated flakes, casseroles, pudding, pies, cakes, patties, breads, soups, beverages, and baby foods (Kays 1985; Truong 1992). Commercial production of these processed products usually begins by transforming sweetpotato roots into a puree. OFSP have successfully been processed into purees that are viscous, but flowable, and can be handled in various processing operations (Truong and others 1995; Coronel and others 2005). However, PFSP have higher dry matter content than OFSP, and potentially different starch properties, which present challenges for the commercial production of puree from this high anthocyanin material. For the PFSP puree to be used as a functional food ingredient, it must flow so that it can be mixed and pumped through processing equipment.

The objectives of this research were to examine the phenolic characteristics of PFSP that have recently been grown in limited commercial production in the United States, and to evaluate the rheological properties of the PFSP purees, to develop a process for producing flowable purees to be utilized as functional ingredients in the food industry.

Materials and Methods

Chemicals

Chlorogenic acid, Folin-Ciocalteu reagent, 2,2-diphenyl-1-picrylhydrazyl (DPPH), and Trolox (2,5,7,8-tetramethylchroman-

MS 20070869 Submitted 11/26/2007, Accepted 3/20/2008. Author Steed is with Dept. of Food Science, and author Truong is with U.S. Dept. of Agriculture, Agricultural Research Service, South Atlantic Area, Food Science Research Unit, North Carolina State Univ., Raleigh, NC 27695-7624, U.S.A. Direct inquiries to author Truong (E-mail: Den.Truong@ars.usda.gov).

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2-carboxylic acid) were purchased from Sigma-Aldrich (Milwaukee, Wis., U.S.A.), and AAPH [2,2'-azobis(2-amidinopropane) dihydrochloride] was purchased from Wako Chemicals USA (Richmond, Va., U.S.A.). All solvents and chemicals were of analytical grade.

Sample preparation of raw and steamed roots

Sweetpotatoes with purple skin and flesh (Stokes Purple cultivar) were procured from Saura Pride Sweetpotatoes (Walnut Cove, N.C., U.S.A.). This new cultivar was coded NC 414 in the germplasm collections of the Sweetpotato Breeding Program, North Carolina State Univ. Two batches of the harvested roots were cured at 30 °C, 85% to 90% relative humidity for 7 d, and stored at 13 °C, 85% to 90% relative humidity. Duplicate samples of the roots ($n = 10$) were taken from the 2 batches for analysis. These roots were hand washed and allowed to air-dry overnight. Each root was cut longitudinally into fourths and divided into 4 groups. Two groups were used to create a raw sample set and two were used for a steamed sample set. To prepare the raw samples, 1 group was peeled and quickly cut into slices of about 0.50- to 0.75-cm thickness while the other group was sliced whole. From the chopped roots about 250-g representative samples were taken and double bagged into quart size Ziploc® bags (Racine, Wis., U.S.A.). These groups formed 3 raw samples: peels, flesh, and whole roots. All samples were put into a -80 °C freezer within 5 min after slicing to minimize pigment degradation. Once frozen, they were removed from the freezer, shattered with a hammer, and quickly weighed out into plastic containers, which were covered with cheesecloth, placed back in plastic bags, and kept frozen at -80 °C until freeze-drying.

The remaining 2 groups were peeled and sliced in the same way and then each sample was steamed for 30 min (100 °C, atmospheric pressure) in a 7.5-L pot outfitted with a steam basket (Home Essentials, Kmart, Troy, Mich., U.S.A.). After steaming, the sweetpotatoes were held in containers with lids until cool to prevent moisture loss. Steamed samples were then homogenized in a Robotcoupe mixer (Model RSI 2YI Ridgeland, Miss., U.S.A.). Representative samples were taken, placed in plastic containers, and frozen at -80 °C, as described previously, to create 3 cooked sample sets: steamed peels, steamed flesh, and steamed whole roots.

Samples were removed from -80 °C storage and placed into a Virtis Genesis 25XL freeze dryer (Gardiner, N.Y., U.S.A.) that operated at -35 to -40 °C. They were allowed to dry for 1 wk, and placed in Ziploc bags to warm up to room temperature. The samples were weighed and ground into powder using a Mr. Coffee® precision coffee grinder (Sunbeam, Boca Raton, Fla., U.S.A.). The powders were placed in sample vials and kept in -80 °C storage until analysis.

Puree production

Puree samples with various dry matter contents (15% to 25%) were adjusted by adding water to the cooked slices. For the lab-scale experiments, steamed slices and water were weighed, put into a 2.4-L food processor (Black and Decker Power Pro II Model FP1500K, Shelton, Conn., U.S.A.), and ground for 2 min to obtain a homogeneous puree. These puree samples were kept at -20 °C for rheological testing.

Puree production was scaled up (Figure 1) to convert 500 kg of PFSP into puree in the Fruit and Vegetable Pilot Plant, Dept. of Food Science, North Carolina State Univ. The roots were tumble washed, sliced to 0.65-cm thickness (Louis Allis Co. Slicer, Milwaukee, Wis., U.S.A.), and steam cooked for 20 min (100 °C, atmospheric pressure) in a thermoscrew steam cooker (Rietz Manufacturing Co., Santa Rosa, Calif., U.S.A.). A ribbon mixer (Keebler Engineering Co., Chicago, Ill., U.S.A.) was used to add water to the slices, which ad-

justed dry matter content to 18%. From the ribbon mixer, sweetpotato puree was then pureed using a hammer mill (Model D, Fitzpatrick Co., Chicago, Ill., U.S.A.) fitted with a 0.15-cm screen. Puree was placed in 5 gallon buckets with lids and frozen at -20 °C until later use.

Duplicate samples were taken at each stage of the pilot-scale puree production process (raw slices, steamed slices, puree), placed into containers, and freeze-dried as described previously.

Analysis of phenolic content and antioxidant activities

Preparation of the extracts. Extraction of polyphenolic compounds from freeze-dried sweetpotato powders was performed using an accelerated solvent extractor (Dionex ASE 200, Sunnyvale, Calif., U.S.A.) equipped with a solvent controller. Three cellulose filters were placed in the bottom of a 22 mL stainless steel extraction cell and covered with 2 g of sea sand (Fisher Scientific, Pittsburgh, Pa., U.S.A.). Sweetpotato powder (0.25 g) was mixed with 26 g of sand, loaded into the cell, and then closed tightly. Extraction parameters for all extracts were set as follows: pressure, 1500 psi; temperature, 100 °C; extraction time, 3 × 5 min cycles; flushing volume, 60%; and nitrogen purge time, 60 s. All powders were extracted with a solvent containing 7% acetic acid in 80% methanol that was purged with nitrogen gas prior to use to prevent phenolic oxidation during the extraction. Extracts were collected in amber glass vials, adjusted to 50 mL volume with solvent, dispersed into 10 mL serum tubes, and kept at -80 °C until analyzed.

Quantification of total phenolics and anthocyanins. The total phenolic content was quantified using a modified Folin-Ciocalteu (FC) method (Singleton and others 1999). Samples and standards (0.25 mL) were diluted in 4 mL of water to which 0.5 mL of the FC reagent was added and allowed to react for 3 min.

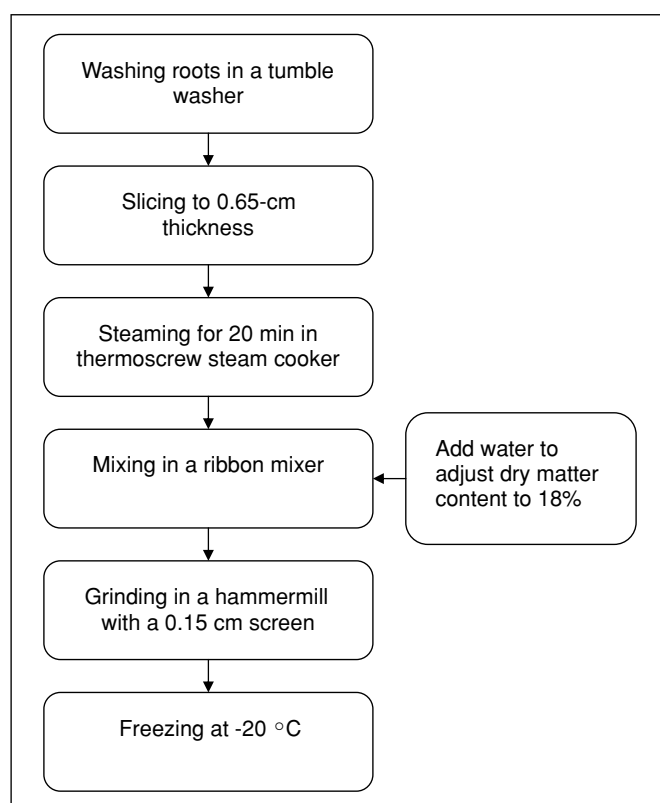


Figure 1—Pilot plant process for production of flowable purees from purple-fleshed sweetpotatoes.

Then, 0.5 mL 1 N sodium carbonate was added and the reaction was carried out for 1 h. Samples were read for absorbance at 725 nm using a Varian spectrophotometer (Cary WinUV Model 300, Palo Alto, Calif., U.S.A.). The spectrophotometer was calibrated with a blank that contained 0.25 mL water instead of sample, along with the same amount of water for dilution, FC reagent, and sodium carbonate solution. Chlorogenic acid was used as the standard; and the total phenolic values were reported in milligrams chlorogenic acid equivalents per 100 g fresh weight (mg CAE/100 g fw).

The total monomeric anthocyanin content was determined using the pH-differential method (Giusti and Wrolstad 2001). Two dilutions were performed on each sample. The first used potassium chloride (0.025 M) at pH 1 and the second was with sodium acetate (0.4 M) at pH 4.5. Samples were diluted so that absorbance readings at 530 nm were less than 1.2. They were allowed to equilibrate for 15 min before absorbance at 530 and 700 nm was recorded using a spectrophotometer calibrated with distilled water as the blank.

The difference in absorbance between pH values and wavelengths was calculated:

$$A = (A_{530\text{ nm}} - A_{700\text{ nm}})_{\text{pH}1.0} - (A_{530\text{ nm}} - A_{700\text{ nm}})_{\text{pH}4.5}$$

The concentration of monomeric anthocyanin pigment was obtained: monomeric anthocyanin pigment (mg/L) = $(A \times \text{MW} \times \text{DF} \times 1000) / (\epsilon \times 1)$, where MW is the molecular weight, DF is the dilution factor, ϵ is the molar absorptivity, and 1 is for a standard 1-cm pathlength. The molecular weight (MW = 449.2) and molar absorptivity ($\epsilon = 26900$) for cyanidin-3-glucoside were used. The total monomeric anthocyanins were reported as milligrams anthocyanins per 100 g fresh weight or dry weight (mg cyanidin-3-glucoside/100 g fw or dw).

Assay of DPPH radical scavenging activity. Antioxidant activity determined by the DPPH assay is based on the methodology described by Brand-Williams and others (1995). Trolox was used as a standard and concentrations ranging from 0 to 500 μM were used to create a standard curve. Samples were diluted 10-fold and then 100- μL sample or standard was added to 1.9 mL of DPPH solution and allowed to react for 3 h. Absorbances of standards and samples were read at 515 nm with a spectrophotometer. The DPPH values were expressed in μmol trolox equivalents per gram fresh weight ($\mu\text{mol TE/g fw}$).

Oxygen radical absorbance capacity (ORAC). The ORAC procedure established by Prior and others (2003) was followed. Fluorescence intensity measurements were performed using a Safire monochromator based microplate reader equipped with Magellan V4-W reader software (Tecan USA, Research Triangle Park, N.C., U.S.A.). Samples were loaded into 96-well transparent Costar polystyrene flat bottom plates (Corning, Acton, Mass., U.S.A.). The concentrations of reagents prepared were the same as described by Prior and others (2003) except that the samples were diluted 100-fold. Wells were filled with 70 μL of phosphate buffer, 60 μL of fluorescein solution, and 60 μL of standard or sample. For blank wells, phosphate buffer was used in place of the sample. The plate was incubated at 37 °C for 15 min before 60 μL of AAPH were rapidly added to each well. Plates were shaken orbitally for 5 s at the start and between 1-min reading intervals. Measurements were performed with 80 cycles using excitation and emission filter wavelengths of 485 and 520 nm, respectively.

ORAC values were calculated using a regression equation $Y = mx + b$ for a linear regression on the range of 6.25 to 100 μmol trolox standards. Y is the concentration and x is the net area under the fluorescence decay curve. The area under the curve was calculated

as follows:

$$\text{AUC} = (0.5 + f_5/f_4 + f_6/f_4 + f_7/f_4 + \dots + f_i/f_4) \times \text{CT}$$

where f_4 is the initial fluorescence reading at cycle 4, f_i is the fluorescence reading at cycle i , and CT is the cycle time in minutes. The net area under the curve was obtained by subtracting the area under the curve for the blank values from the curves of samples and standards. ORAC values were expressed in μmole trolox equivalents per gram of fresh weight ($\mu\text{mol TE/g fw}$).

Color measurements. Hunter L^* , a^* , and b^* values were measured with a Hunter colorimeter (D25/DP9000 Tristimulus Colorimeter, Hunter Associate Laboratories Inc., Reston, Va., U.S.A.). The cooked sweetpotato samples were filled into a 35-mm petri dish, covered, and pressed against the surface to remove air bubbles. The colorimeter was calibrated against a standard white tile ($L^* = 92.78$, $a^* = -0.73$, $b^* = -0.13$) and sample measurements were taken at 3 different locations, with duplicates performed for each sample. Averages of these readings are reported. Hue angle (h°) was calculated using $\arctan(b^*/a^*)$ and chroma (C^*) was calculated using $[a^{*2} + b^{*2}]^{1/2}$.

Moisture determination and pH measurements. Moisture content was determined based on the AOAC oven-drying method at 105 °C for 24 h. Moisture content of the samples was also calculated from the initial and final weight of the freeze-dried samples. The pH of sweetpotato samples was measured by performing 2 dilutions on the sample. First, dry matter content was adjusted to 18% by adding distilled water to the flesh and whole samples to create the same dilution used in scaled-up puree production. Then all samples were diluted 1:1 with distilled water. Samples were homogenized using a Tissumizer (Tekmar, Cincinnati, Ohio, U.S.A.) and the pH was measured using an Accumet AR50 pH meter (Fisher Scientific).

Rheological testing

Rheological properties of the lab-scale puree samples were evaluated using a stress-controlled ATS Stresstech Rheometer (Rheosystems, Bordentown, N.J., U.S.A.) outfitted with serrated cup and bob geometry. Samples were covered with a thin layer of mineral oil to prevent moisture loss and presheared at 20 per second for 30 s before testing began. Shear rate sweeps were performed at 5, 25, 70, and 90 °C with shear rate ramped from 1 to 300 per second. At each temperature change, the samples were allowed to equilibrate for 60 s. The OFSP puree from Beauregard cultivar (George Foods, Pembroke, N.C., U.S.A.) was measured under the same conditions. Apparent viscosity measurements at 25 °C were compared between the orange puree, as a standard, and the purple puree samples.

The puree samples from the scale-up pilot plant experiments were also evaluated and the results were used to model the behavior of the puree using the Herschel-Bulkley model:

$$\sigma = \sigma_0 + K\gamma^n$$

where σ is the shear rate, σ_0 is the yield stress, γ is shear rate, K is the consistency coefficient, and n is the flow behavior index (Steffe 1996).

Statistical analysis

The experiments were performed with 2 replicates, and duplicate samples were taken from each replicate for all analyses. Group differences were evaluated using analysis of variance (ANOVA) F -tests using SAS version 8.1 (SAS Inst. Inc., Cary, N.C., U.S.A.) with $P < 0.05$ considered to be a statistically significant difference.

Means were separated by the Student–Newman–Keuls (SNK) procedure. This was chosen due to the unequal sample sizes of the lab samples, and this procedure accounts for that by using the harmonic mean. The SNK procedure is less conservative than other methods of means separation, which means that it is more likely to declare a difference between values. Color data were evaluated using Tukey's studentized range because sample sizes were equal. Regression analysis was carried out for correlation determination with a significant R^2 having $P < 0.05$.

Results and Discussion

Total phenolics

The total phenolic content of the samples from the lab-scale experiment ranged from 401.6 mg CAE/100 g fw for puree to 1483.7 mg CAE/100 g fw for raw peels (Table 1). The phenolic content of the peels was significantly higher from the flesh and whole roots for both raw and steamed samples. The peel samples had at least 3 times the phenolic content of flesh and whole roots. Steaming resulted in a significant decrease ($P < 0.05$) in phenolic content of the peels but this effect was not observed for the flesh and whole roots. In sweetpotatoes, the peels only contribute to 10% to 15% of the total weight of the roots; therefore the high phenolic content of the peels did not have any effect on the total phenolic contents of the whole root. These results are in accordance with a previous report for the raw and steamed tissues of OFSP (Truong and others 2007).

As expected, the PFSP examined in this study had much higher total phenolics than OFSP. Truong and others (2007) reported the total phenolic contents for the peels and flesh of Beauregard cultivar ranged from 78.6 to 181.4 mg CAE/100 g fw. The total phenolic content of the PFSP peels was comparable with purple corn and red-fleshed sweetpotatoes that have reported values of 1756 mg CAE/100 g fw and 945 mg CAE/100 g fw, respectively (Cevallos-Casals and Cisneros-Zevallos 2003). However, these total phenolic values are much lower than the amount of 2556 mg CAE/100 g fw reported for some berry fruits such as wild chokeberries (Zheng and Wang 2003).

For the pilot plant experiment, the phenolic content of the raw slices was significantly lower than that of the steamed slices (Table 1). This effect was not observed in any sample set of the laboratory-scale experiment described previously. These results can be attributed to the difference in sampling methods for the 2 experiments. For the lab-scale experiment, the raw samples were frozen at -80°C within 5 min after slicing which likely minimized enzymatic pigment degradation. However, in the pilot plant exper-

iment the representative sliced samples taken throughout the processing scheme were kept in Ziploc bags at room temperature and exposed to air and oxygen for a much longer time, about 3 to 4 h. Jang and others (2005) isolated polyphenoloxidase (PPO) in purple-fleshed potatoes and found that the enzyme is most active at room temperature and degraded at temperatures $> 70^\circ\text{C}$. Ascorbic acid has been shown to inhibit the decrease in caffeic acid derivatives of sweetpotatoes, and this inhibition supports the involvement of PPO in degradation of phenolic compounds (Takenaka and others 2006). Therefore, thermal and/or chemical treatment to inactivate PPO should be applied to maintain high retention of the phenolic components during processing.

The puree samples were significantly lower in total phenolic content than all other samples presented in Table 1. Adjustment of dry matter content to 18% by adding water to the steamed slices diluted the phenolic components. However, we found that adding water was necessary to produce PFSP purees that are flowable for industrial-scale operations. When examined on a dry weight basis, the total phenolic content of the puree was not statistically significant ($P < 0.05$) from raw and steamed whole roots. Klopotek and others (2005) processed strawberries to many different products and found a significant decrease in the total phenolic content from 257.1 mg GAE/100 g fw in fresh strawberries to 73.6 mg GAE/100 g fw for strawberry puree.

Total monomeric anthocyanins

Anthocyanins are the most important group of phenolic compounds present in PFSP. They contribute to the characteristic color and have been linked to antihyperglycemic, anticancer, and antimutagenic health benefits (Yoshimoto and others 1999; Matsui and others 2002; Suda and others 2003). Since they are a subcategory of phenolic compounds, the anthocyanin content of the samples analyzed was expected to follow the same trends as seen in the total phenolic assays. The total monomeric anthocyanins range from 57.5 mg/100 g fw for puree to 174.7 mg/100 g fw for raw peels. The anthocyanin content in the peels was about 1.3 to 1.7 times higher than the flesh and whole roots (Table 1). However, there was no significant difference ($P > 0.05$) in the total anthocyanin content of flesh and whole root samples due to the low contribution of peels to overall weight as previously discussed. Steaming resulted in significant decreases ($P < 0.05$) in the anthocyanin content of all the laboratory experiment samples. A higher total monomeric anthocyanin value of steamed slices compared to raw slices for the samples from the pilot plant experiments was probably due to the long exposure of the sample to ambient conditions.

Table 1 – Total phenolic, anthocyanin, and antioxidant values of purple-fleshed sweetpotato samples.

Sample	Treatment	Dry matter (%)	TP	TMA	DPPH	ORAC
Lab scale						
Peel	Raw	28.8	1483.7 \pm 18.6 ^{a,A}	174.7 \pm 3.3 ^a	87.4 \pm 2.0 ^a	78.2 \pm 1.0 ^a
Flesh	Raw	37.7	408.1 \pm 13.9 ^{de}	101.5 \pm 2.5 ^b	75.5 \pm 1.6 ^{bc}	58.5 \pm 1.3 ^b
Whole	Raw	36.9	469.9 \pm 13.8 ^d	107.8 \pm 1.8 ^b	79.8 \pm 1.9 ^b	58.7 \pm 1.2 ^b
Peel	Steamed	24.0	1298.1 \pm 43.3 ^b	109.8 \pm 5.2 ^b	77.0 \pm 1.0 ^{bc}	71.5 \pm 2.2 ^a
Flesh	Steamed	36.4	401.6 \pm 24.1 ^{de}	80.2 \pm 5.5 ^c	77.1 \pm 1.6 ^{bc}	53.1 \pm 1.7 ^{bc}
Whole	Steamed	37.0	465.9 \pm 13.4 ^d	84.6 \pm 2.7 ^c	75.5 \pm 1.8 ^{bc}	60.0 \pm 1.1 ^b
Pilot plant scale						
Slices	Raw	29.6	353.4 \pm 14.5 ^{ef}	68.7 \pm 7.1 ^d	66.6 \pm 1.7 ^d	49.0 \pm 3.0 ^{bc}
Slices	Steamed	28.2	570.8 \pm 8.9 ^c	83.0 \pm 2.7 ^c	70.8 \pm 1.6 ^{dc}	46.2 \pm 2.5 ^c
Puree ^B		18.1	313.6 \pm 4.6 ^f	57.5 \pm 1.5 ^e	47.0 \pm 2.6 ^e	26.4 \pm 1.3 ^d

TP = total phenolics values expressed in mg CAE/100 g fw; TMA = total monomeric anthocyanins expressed as mg cyanidin-3-glucoside/100 g fw; DPPH values expressed as $\mu\text{mol TE/g fw}$; ORAC values expressed as $\mu\text{mol TE/g fw}$.

^AValues reported are means of 2 replicates \pm the standard error of the mean. Subscripts signify significance based on ANOVA F -tests with Student–Newman–Keuls means separation.

^BPuree made by adjusting slices to 18% dry matter.

A decrease in the total monomeric anthocyanin values of steamed samples with reference to raw sweetpotato samples (Table 1) is in contrast to the previous reports. Teow (2005) reported higher total phenolic and total monomeric anthocyanin contents for the steamed samples compared to the chopped samples of the raw roots from most of the PFSP clones evaluated. Yang and Gadi (2006) also reported that steaming a PFSP cultivar, Terlaje, for 0.5 h increased anthocyanin content. The results in our study are attributable to the high activity of PPO that was previously discussed. The same reasoning can also be used to explain why the raw pilot plant slices have significantly lower anthocyanins than the steamed slices. The lab-scale sampling procedure quickly transferred sliced roots to -80°C storage, which is believed to have stopped enzymatic degradation of the pigments catalyzed by PPO.

Anthocyanins are present in a wide range of fruits, including many types of berries, and some vegetables. Black currant, blueberries, and red cabbage are the common food commodities that are known to have higher anthocyanin contents, ranging from 322 ± 40.8 to 476 ± 115 mg anthocyanins/100 g fw, while red-fleshed sweetpotatoes have 182 ± 2 mg anthocyanins/100 g fw (Cevallos-Casals and Cisneros-Zevallos 2003; Wu and others 2006). The anthocyanin contents for PFSP in the study were lower than these foods, but compared well with sweet cherries, grapes, plum, raspberries, eggplant, and red radishes, showing that they fall in the middle of the spectrum of high anthocyanin fruits and vegetables (Wu and others 2006).

The anthocyanin content of the PFSP puree, on a fresh weight basis, was significantly lower than that of the steamed slices (Table 1). However, on a dry weight basis, the content of the PFSP puree was 305.5 ± 7.9 mg anthocyanins/100 g dw, which was not significantly different ($P > 0.05$) from the value of steamed slices (283.1 ± 9.3 mg anthocyanins/100 g dw). Therefore, steam cooking and pureeing in the pilot plant process did not decrease total monomeric anthocyanins, but lower anthocyanin content on the fresh weight basis was due to the dilution of the steamed slices with water to produce flowable puree. PFSP puree was on the lower end of the anthocyanin spectrum with a content of 57.5 ± 1.5 mg anthocyanins/100 g fw, which is comparable to black bean, red onion, and strawberries reported by Wu and others (2006).

Color values

The difference in anthocyanin content between samples is reflected in the Hunter L^* , a^* , b^* values and summarized in Table 2. Differences for each attribute among the samples were significant ($P < 0.05$). L^* is a lightness index and ranges from 0 to 100 with 0 representing black and 100 representing white. The PFSP puree was the darkest sample while the whole steamed roots were darker than steamed flesh. The utilization of the whole roots would not increase the total phenolic and anthocyanin content due to the small weight contribution of the peels as previously discussed. However, it resulted in darker color of the PFSP puree. Truong and others (2007) reported similar effects in processing of the OFSP puree. The intensity of red color is represented by a^* value while blue color is represented by a negative b^* value.

The puree samples were the most intense for all color attributes, which leads to an increased chroma (C^*) value and hue angle (h°) that signifies more of a blueish purple. Earlier studies suggested that the higher saturation and different hue were caused by a higher pH, which is known to cause darker purple and blue colors (Suda and others 2003). However, the pH measurements for all samples were about 6.0. Instead, the darker color of the puree may be due to metal ions present in the tap water used to dilute steamed slices in the pilot plant puree process. These ions could potentially form complexes with the anthocyanins in PFSP and lead to differences in color. Cornflower anthocyanin structure has a metal complex formed between anthocyanins and a ferric ion. This complex causes the characteristic blue color of the cornflower, but its absence in roses makes the same anthocyanin appear red (Takeda 2006).

Purple color in sweetpotatoes is due to anthocyanins that are mono- or diacylated forms of peonidin and cyanidin (Terahara and others 2000, 2004). Yoshinaga and others (1999) found that PFSP clones fell into 2 main color groups based on their b^*/a^* ratio. Clones that have ratios less than -1.4 are blue dominant, which tend to have more cyanidin than peonidin while clones with ratios greater than -1.1 are red dominant and have more peonidin. Based on this finding, the samples evaluated in this study were more peonidin rich since the b^*/a^* ratios ranged from -0.59 to -0.51 . Further studies on isolation and identification of anthocyanin compounds in these PFSP materials need to be conducted.

Antioxidant activity

Based on the DPPH assay, raw peels exhibited the highest antioxidant activity with $87.4 \mu\text{mol TE/g fw}$ while the lowest antioxidant activity is represented by puree with $47.0 \mu\text{mol TE/g fw}$. Raw peels had almost twice the antioxidant activity of puree on a fresh weight basis. There was no significant difference in DPPH values among the raw and steamed samples for both flesh and whole roots (Table 1). On a dry weight basis, the DPPH radical scavenging activity of puree was comparable to all other samples except for raw and steamed peels, which were about 1.3 times greater. This range of DPPH values was higher than the DPPH radical scavenging activity ranging from 8.6 to $49.0 \mu\text{mol TE/g fw}$ for a group of 16 purple-fleshed cultivars reported by Oki and others (2002). OFSP (cultivar Beauregard) have lower DPPH values, ranging from about $2.0 \mu\text{mol TE/g fw}$ for flesh to $7.1 \mu\text{mol TE/g fw}$ for peels and as great as $38.2 \mu\text{mol TE/g fw}$ for leaves (Truong and others 2007).

Raw peels also had the highest ORAC value of $78.2 \mu\text{mol TE/g fw}$, while the puree sample had the lowest at $26.4 \mu\text{mol TE/g fw}$ (Table 1). Based on these values, puree is capable of a third of the amount of radical scavenging capacity as peels, and about half as much as flesh and whole root samples on a fresh weight basis. However, on a dry weight basis, puree had the same level of radical scavenging activity as all samples except for raw and steamed peels. Statistical analysis showed that antioxidant activities of the raw and steamed samples of flesh and whole roots were not statistically different ($P > 0.05$, Table 1). The range of ORAC values for PFSP (Table 1) compared well with a range of 35.4 to $61.8 \mu\text{mol TE/g fw}$

Table 2—Color data for selected purple-fleshed sweetpotato samples.

Sample	L^*	a^*	b^*	Hue angle	Chroma
Steamed flesh	$26.0 \pm 0.2^{\text{a,A}}$	$17.7 \pm 0.2^{\text{c}}$	$-10.4 \pm 0.1^{\text{b}}$	$-30.6 \pm 0.4^{\text{b}}$	$20.5 \pm 0.2^{\text{b}}$
Steamed whole	$24.2 \pm 0.1^{\text{b}}$	$18.5 \pm 0.3^{\text{b}}$	$-9.9 \pm 0.1^{\text{a}}$	$-28.3 \pm 0.5^{\text{a}}$	$21.0 \pm 0.2^{\text{b}}$
Puree	$20.3 \pm 0.1^{\text{c}}$	$26.2 \pm 0.1^{\text{a}}$	$-13.3 \pm 0.1^{\text{c}}$	$-26.9 \pm 0.2^{\text{a}}$	$29.4 \pm 0.1^{\text{a}}$

^AValues reported are means of 2 replicates \pm standard error of the means. Means with different letters differed significantly ($P < 0.05$) and are separated by Tukey's studentized range procedure.

for fruits with high antioxidant activity, such as blackberries, cultivated blueberries, sweet cherries, raspberries, and strawberries (Wu and others 2004).

The antioxidant activities assayed by ORAC and DPPH showed a significant correlation ($R^2 = 0.84$, $P < 0.05$). The ORAC values were also significantly correlated ($P < 0.05$) with total phenolic ($R^2 = 0.59$) and total monomeric anthocyanin contents ($R^2 = 0.71$). These results are in accordance with previous findings on significant correlations among the antioxidant activities by ORAC and DPPH methods, total phenolic and anthocyanin contents of various food commodities, including purple-fleshed sweetpotatoes (Awika and others 2003; Teow and others 2007).

Flow properties of PFSP purees

In an initial pilot plant-scale experiment, the cooked slices of the PFSP formed a sticky material that clogged a hammer mill during the attempted puree formation. Unlike the OFSP, the comminuted material from PFSP was paste-like and could not flow through the largest mesh fitted to the hammer mill. The problem was likely due to the high dry matter content of PFSP. As shown in Table 1, PFSP had 28% to 38% dry matter, while OFSP were reported with about 18% to 21% dry matter (Truong and others 2007; Grabowski and others 2008). Furthermore, PFSP could have high levels of starch with pasting, swelling, and thermal properties, which are different from the starch of OFSP. Walter and others (2000) reported a variation in thermal and rheological properties of sweetpotato starches isolated from high and low dry matter cultivars. Therefore, the processing hurdle in pureeing the PFSP could be overcome by either addition of water to decrease the solid and starch levels in the material, amylase hydrolysis of starch components, or a combination of the 2 treatments. For cost-effective reasons, water addition was taken as an initial approach in processing of PFSP purees.

In the lab-scale experiments, PFSP purees with dry matter content of 15% to 25% were prepared with water addition. Samples with dry matter content greater than 25% were too thick for flowable puree. Flow curves of PFSP purees with reference to commercial puree manufactured from the OFSP are shown in Figure 2. The OFSP purees are relatively thick and have been reported to have an apparent viscosity of 5.1 Pa s at 25 °C with a shear rate of 50 per second (Coronel and others 2005). However, the OFSP puree is flowable and has been used in many food processing applications including continuous flow microwave and aseptic processing (Coronel and others 2005). The PFSP purees adjusted to 21% dry matter

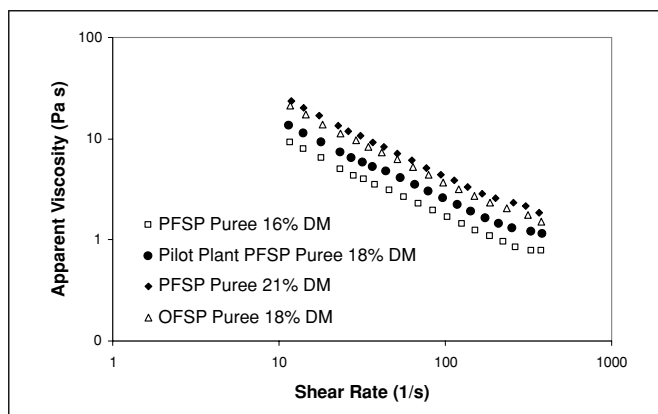


Figure 2—Apparent viscosity of purple-fleshed sweetpotato purees at different levels of dry matter content (DM) as compared to commercial orange-fleshed sweetpotato puree at 25 °C. Data points are the means of 2 replicates.

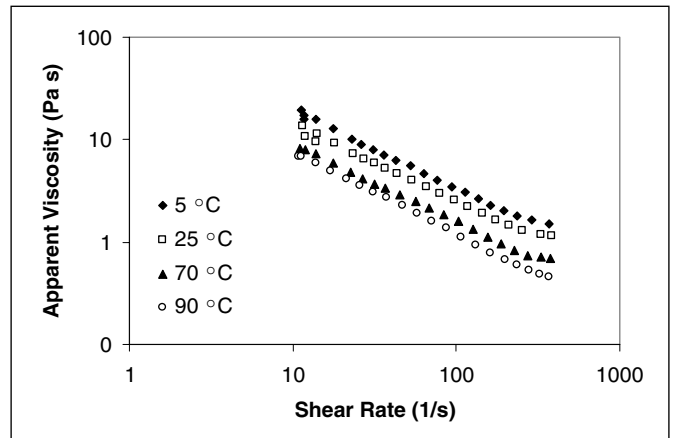


Figure 3—Apparent viscosity of purple-fleshed sweetpotato puree (18% dry matter content) at different temperatures. Data points are the means of 2 replicates.

showed a viscosity curve that closely mimicked the flow properties of OFSP puree (Figure 3). When the puree process was scaled up in the pilot plant, water was added based on calculations aimed at mimicking the 21% dry matter PFSP puree created on the lab scale. However, the resulting PFSP puree had 18% dry matter, and its viscosity is shown in Figure 2. A lower dry matter content could result from using a less accurate scale in the pilot plant as compared to the scales in the laboratory. The scale in the pilot plant that could withstand processing conditions measured to 1 decimal point, and this value was rounded to a 0 or a 5. This could lead to inaccuracies in weighing the amount of water needed to produce a 21% dry matter puree. As a result of the lower dry matter content in the pilot plant PFSP puree, the viscosity was slightly lower than OFSP puree (Figure 2). A less viscous puree is easier to work with from a processing standpoint, and the final dry matter content was kept above 16%. This was the lowest dry matter content evaluated because at concentrations lower than 16%, the purees had an observable degree of syneresis during storage, which was an undesirable attribute.

Figure 3 shows the flow curves of PFSP puree adjusted to 18% dry matter content at 4 different temperatures; 5, 25, 70, and 90 °C. Apparent viscosity decreased as temperature increased, and this same behavior has been reported for OFSP purees by Kyereme and others (1999). Furthermore, several researchers have found that OFSP puree exhibits non-Newtonian, pseudoplastic behavior with a yield stress that fits the Herschel–Bulkley model (Rao and others 1975; Kyereme and others 1999; Grabowski and others 2008). The flow behavior of a PFSP puree with 18% dry matter was modeled using the Herschel–Bulkley model, and the yield stress values ranged from 102.5 ± 22.1 Pa at 5 °C to 38.7 ± 6 Pa at 90 °C. Flow behavior index (n) was consistent and ranged from 0.35 to 0.41 while consistency coefficients (K) decreased from 44.5 ± 17.0 Pa s^{*n*} at 5 °C to 14.5 ± 2.2 Pa s^{*n*} at 90 °C (Table 3). Both the consistency coefficient and flow behavior index values for PFSP purees were out of the ranges of 2.8 and 21.5 Pa s^{*n*} and 0.20 to 0.33, respectively, that were reported by Kyereme and others (1999) for orange sweetpotato purees at 15 to 90 °C. However, these results are in accordance with the previous values on flow properties of purees from OFSP (Coronel and others 2005; Grabowski and others 2008). Similar consistency coefficient values of 1.8 to 24.8 Pa s^{*n*} were reported by Rao and others (1975) for 7 different orange sweetpotato cultivars. These investigators also reported flow behavior index values from 0.33 to 0.56 at 25 °C, which were close to the values found for PFSP puree in this study.

Table 3—Yield stress (σ_0), flow behavior index (n), and consistency coefficient (K) of 18% dry matter purple-fleshed sweetpotato puree determined by Herschel-Bulkley modeling.

Temperature (°C)	σ_0 (Pa s)	n	K (Pa s ^{n})
5	102.5 ± 22.1 ^{a,A}	0.37 ± 0.04 ^a	44.5 ± 17.0 ^a
25	81.0 ± 16.3 ^b	0.41 ± 0.05 ^a	26.3 ± 10.7 ^a
70	45.4 ± 10.8 ^c	0.35 ± 0.02 ^a	22.7 ± 9.8 ^a
90	38.7 ± 6.6 ^d	0.36 ± 0.02 ^a	14.5 ± 2.2 ^a

^AValues reported are means of 2 replicates ± standard error of the means. Means with different letters differed significantly ($P < 0.05$) and are separated by Tukey's Studentized range procedure.

Conclusions

Purple-fleshed sweetpotatoes have phenolic components in competitive levels with other food commodities known to be good sources of antioxidants. Both raw and steamed PFSP had high phenolic and anthocyanin content. To make a flowable puree that will have applications in the food industry, water must be added to the steamed PFSP to reduce the dry matter content to 18%–21%. The flowable PFSP puree exhibited shear thinning behavior similar to the commercial purees from OFSP, and its phenolic content was within the range of the high antioxidant purees from other fruits and vegetables. With its flowability, attractive purple color, and high antioxidant activity, the PFSP puree has potential as a functional food ingredient in various food systems, including beverages, soups, baby foods, bakery products, frozen foods, and ice cream.

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