Chemical Constituents of Sweetpotato Genotypes in Relation to Textural Characteristics of Processed French Fries

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Abstract: Sweetpotato French fries (SPFF) are growing in popularity, however limited information is available on SPFF textural properties in relation to chemical composition. This study investigated the relationship between chemical components of different sweetpotato varieties and textural characteristics of SPFF. Sixteen sweetpotato genotypes were evaluated for (1) chemical constituents; (2) instrumental and sensory textural properties of SPFF; and (3) the relationship between chemical components, instrumental measurements, and sensory attributes. Dry matter (DM), alcohol-insoluble solids (AIS), starch, sugar, and oil content, and also α- and β-amylase activities were quantified in raw sweetpotatoes and SPFF. Peak force and overall hardness describing instrumental textural properties of SPFF were measured using a texture analyzer. Descriptive sensory analysis was conducted and 10 attributes were evaluated by a trained panel. Results showed that DM, AIS, and starch content in raw sweetpotatoes were significantly correlated ($P < 0.05$) with instrumental peak force and overall hardness ($r = 0.41$ to 0.68), and with sensory surface roughness, hardness, fracturability, and crispness ($r =$ 0.63 to 0.90). Total sugar content in raw sweetpotatoes was positively correlated with sensory smoothness and moistness ($r = 0.77$), and negatively correlated with instrumental peak force and overall hardness ($r = -0.62$ to -0.69). Instrumental measurements were positively correlated with sensory attributes of hardness, fracturability, and crispness ($r = 0.68$ to 0.96) and negatively correlated with oiliness, smoothness, moistness, and cohesiveness ($r = -0.61$ to -0.91). Therefore, DM, AIS, starch, and total sugar contents and instrumental measurements could be used as indicators to evaluate sweetpotato genotypes for SPFF processing.

Keywords: descriptive sensory analysis, French fries texture, instrumental measurement, *Ipomoea batatas*, sweetpotato French fries

Practical Application: In recent years, sweetpotato French fries (SPFF) have grown in popularity, but limited information is available on SPFF textural properties in relation to the differences in chemical constituents among sweetpotato varieties. This study demonstrated that sensory texture attributes of SPFF varied widely and were significantly correlated with chemical components such as dry matter, starch, and total sugar contents of raw sweetpotatoes and instrumental texture measurements of SPFF. The knowledge generated from this study will benefit the food industry and breeding programs with the selection of sweetpotato varieties for improved SPFF quality.

Introduction

Sweetpotato (*Ipomoea batatas* L.) is an economically important crop and an excellent source of carotene, dietary fiber, and vitamins. There are numerous sweetpotato genotypes with different sensory characteristics such as taste, texture, and flesh color. Varieties with high dry matter (DM) content have a firm and mealy texture after cooking, although those with low DM content have a soggy texture after cooking (Truong and others 2011). Although commonly processed sweetpotato products are flours, starches, juices, and purees, new processed products such as French fries have been developed in the past several decades. Recently, consumer demand for sweetpotato French fries (SPFF) has increased. Currently, SPFF are processed using the existing sweetpotato cultivars that were developed for the fresh root market, but SPFF produced from these existing cultivars have an undesirable soggy texture. Therefore, there is a need for the development of sweetpotato genotypes that will produce high-quality SPFF.

Previous studies on SPFF have focused on processing conditions in relation to SPFF quality. Walter and others (1992) reported that increased firmness of SPFF could be achieved by sweetpotato tissue acidification. In a study with purple-fleshed SPFF, SPFF without a prior blanching treatment had the highest crust hardness and poor texture quality, which was described as hard or rubbery (Oner and Wall 2012). In addition, pre-drying of the blanched strips before frying resulted in increases of DM content and improvement of the SPFF texture (Walter and Hoover 1986; Truong and others 2014).

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Table 1–Chemical components of raw sweetpotatoes.[a]

Genotype	Flesh color	DM[b] (%)	AIS[c] (g/100 g)	Starch (g/100 g)	Total sugar (g/100 g)	α-Amylase activity (CU/100 g)	β-Amylase activity (U/100 g)
NC08-036	Orange	18.59 i	11.58 k	6.02 k	6.49 a	20.96 fgh	618.91 a
Evangeline	Orange	19.90 hi	13.54 j	7.99 j	5.40 b	34.34 de	228.81 de
NC13-487	Orange	20.55 gh	16.33 i	10.55 hi	2.72 gh	29.16 efg	279.72 cd
NC05-198	Orange	20.99 gh	16.36 i	12.36 g	3.42 ef	51.52 bc	354.48 b
Beauregard	Orange	21.25 gh	19.06 h	10.87 h	3.74 de	16.15 h	151.78 fg
Covington	Orange	22.00 g	17.17 i	9.74 i	4.69 c	130.54 a	128.09 fg
NC13-1012	Orange	24.95 f	20.16 gh	14.26 f	3.47 ef	33.78 de	46.18 hi
NC09-122	Orange	25.24 ef	20.20 gh	14.76 f	4.26 cd	18.27 gh	182.53 ef
NC13-1001	Orange	26.08 def	22.27 f	16.45 e	3.04 fg	63.00 b	235.41 de
Porto Rico	Orange/yellow	26.79 de	22.50 f	16.29 e	3.86 de	19.51 gh	372.65 b
Bonita	Cream	26.90 d	23.65 e	17.69 d	2.71 gh	14.06 h	222.13 de
NC13-1027	Orange	29.44 c	22.98 ef	17.95 d	4.54 c	12.83 h	5.97 i
NC13-1004	Yellow	31.81 b	27.96 d	21.82 b	2.94 fg	51.60 bc	110.49 gh
NCDM04-197	Yellow	32.88 b	31.42 c	20.18 c	1.37 i	20.65 fgh	313.71 bc
Suwon122	Yellow	33.28 b	32.78 b	20.09 c	2.15 h	42.61 cd	224.99 de
NCDM04-001	Yellow	37.20 a	36.65 a	23.40 a	1.22 i	30.78 ef	3.93 i

[a]Sweetpotatoes were grown in North Carolina, U.S.A., cured for 7 d at 30 °C, 85% to 90% relative humidity, and stored for 7 or 4 mo at 14 °C, 80% to 90% relative humidity. All data are presented on a fresh-weight basis. Values within each column followed by different inline lowercase letters are statistically different ($\alpha = 0.05$).
[b]DM, dry matter.
[c]AIS, alcohol-insoluble solids.

Physico-chemical properties of sweetpotato varieties can have profound effects on SPFF textural properties and sensory profiles. Alcohol-insoluble solids (AIS) and sugar contents in SPFF were highly correlated with sensory intensity of first-bite moistness (Walter and others 1997). Low DM was related to perceived softness of SPFF (Oner and Wall 2012). However, cell size, intercellular volume, and specific gravity did not affect instrumental firmness of SPFF (Walter and others 1997). The SPFF products processed from soft-sweet type sweetpotatoes were soft and moist, with few particles and a high degree of mass cohesion. They were easy to swallow with an oily mouth feel, but consumers disliked the 1st-bite moistness and mass cohesiveness of the texture (Walter and others 1997). In a study on restructured SPFF, Walter and others (2002) reported that sensory hardness and density were highly correlated with the value of instrumental measurements (puncture, 3-point bending, Kramer shear test), whereas cohesiveness, oiliness, and moistness were negatively correlated. However, there is no comprehensive report on sensory texture attributes and evaluation techniques for SPFF.

Overall, information on chemical and textural properties of SPFF processed from different sweetpotato varieties is limited. Many studies on textural properties and sensory characteristics of white potato French fries (WPFF) have been conducted over the years (Miranda and Aguilera 2006), but the findings may not be applicable to SPFF because the 2 commodities are different botanically and chemically. This study investigated the relationship between chemical components of different sweetpotato varieties and textural characteristics of SPFF. Sixteen sweetpotato genotypes with varying flesh color and DM content were evaluated regarding: (1) chemical constituents in raw sweetpotatoes and SPFF; (2) instrumental textural properties and sensory textural characteristics of the SPFF; and (3) the relationship between chemical components, instrumental texture measurements, and sensory attributes.

Materials and Methods

Sweetpotato genotypes

All sweetpotato genotypes used in this study were grown at the Horticultural Crops Research Station (Clinton, N.C., U.S.A.). Sixteen genotypes from the Sweetpotato Breeding and Genetics Program at North Carolina State Univ. (NCSU) were selected for the experiments (Table 1). Of those genotypes, 10 genotypes were orange-fleshed, 1 was orange/yellow-fleshed, 1 was cream-fleshed, and 4 were yellow-fleshed. Nine genotypes (NC08-036, Evangeline, Beauregard, Covington, NC09-122, Porto Rico, NCDM04 to 197, Suwon122, NCDM04 to 001) were harvested in 2014, cured at 30 °C and 85% to 90% relative humidity for 7 d, and stored for 7 mo at 14 °C, 80% to 90% relative humidity. Another 7 genotypes (NC13-487, NC05-198, NC13-1012, NC13-1001, NC13-1027, Bonita, NC13-1004) were harvested in 2015, cured and stored for 4 mo under similar conditions.

Processing of sweetpotato French fries

Ten to 12 raw sweetpotato storage roots were randomly selected, washed, tempered as whole roots in tap water at 70 °C for 45 min, and cut into strips of 0.9 × 0.9 cm using a manual French fry cutter (model 29; Vollrath, Bloomfield, Ind., U.S.A.). Strips with skin on the edges were not used in this study and the ends of strips with skins were cut off. The strips (1 kg) were blanched in tap water at 75 °C for 7 min, pre-dried at 65 °C for 10 min using a convection dryer (Food Dehydrator; The Sausage Maker Inc., Buffalo, N.Y., U.S.A.), then par-fried in 22 L canola oil at 185 °C for 75 s using an electric fryer (1ER50 Series; Vulcan-Hart Co., Louisville, Ky., U.S.A.), and placed on absorbent paper towels. The par-fried strips after cooling were kept at −20 °C until final frying. For final frying, the frozen strips (300 g) were fried in canola oil at 177 °C for 150 s using the electric fryer, and placed on absorbent paper towels. The processing conditions were determined based on the previous reports on French fries prepared from potatoes and sweetpotatoes (Walter and others 1997; Parker and others 2012). The experiment was conducted with 2 replications of sweetpotato roots obtained from 2 different lots for each genotype.

Sample preparation for chemical analysis

DM, sugars (glucose, fructose, and sucrose), AIS, starch content, and α- and β-amylase activities were analyzed in raw sweetpotatoes. Moisture, oil, AIS, starch, and sugar (glucose, fructose, sucrose, and maltose) contents were measured in SPFF.

Table 2–Chemical components of sweetpotato French fries.[a]

Genotype	Moisture (%)	Oil (%)	AIS[b] (g/100 g)	Starch (g/100 g)	Total sugar (g/100 g)
NC08-036	57.58 ab	11.02 abc	30.82 k	11.56 g	10.16 a
Evangeline	58.33 a	7.86 cde	33.07 j	12.74 g	7.74 b
NC13-487	50.95 cde	7.73 de	47.08 ef	16.00 f	4.16 fg
NC05-198	56.68 ab	6.75 e	42.54 g	17.89 ef	3.32 gh
Beauregard	57.81 ab	9.88 abcde	36.52 i	18.88 e	5.65 de
Covington	55.49 abc	10.46 abcd	36.42 i	15.79 f	6.85 bc
NC13-1012	50.25 de	9.78 abcde	46.79 ef	19.00 e	5.20 ef
NC09-122	54.74 abcd	8.63 cde	40.17 h	20.46 e	6.45 cd
NC13-1001	45.06 f	9.23 bcde	53.66 c	25.16 d	4.39 fg
Porto Rico	46.00 ef	12.41 ab	48.50 ef	25.25 d	5.75 cde
Bonita	53.12 bcd	6.78 e	45.91 f	23.32 d	3.29 gh
NC13-1027	47.15 ef	7.11 e	51.39 d	25.76 d	2.44 h
NC13-1004	43.66 f	8.16 cde	55.59 c	30.65 c	3.72 g
NCDM04-197	42.64 f	8.02 cde	54.13 c	31.25 c	3.89 g
Suwon122	36.91 g	12.61 a	59.76 b	35.48 b	4.03 g
NCDM04-001	35.73 g	8.90 cde	64.19 a	41.44 a	0.35 i

[a]All data are presented on a fresh-weight basis. Values within each column having different inline lowercase letters are statistically different ($\alpha = 0.05$).
[b]AIS, alcohol-insoluble solids.

Dry matter content. Raw sweetpotatoes were peeled and cut into 1.5-mm slices using a Hobart food processor (Model FP150; Hobart, Troy, Ohio., U.S.A.). The sliced sweetpotatoes (300 g) were freeze-dried for 4 to 5 d until reaching a constant weight using a VirTis Genesis 25XL freeze-dryer (Gardiner, N.Y., U.S.A.), operated at −35 to −40 °C, and the DM content was determined by the difference in weight before and after freeze-drying (Rommens and others 2010). The dried raw sweetpotato samples were pulverized using a mill (model 1093; Foss Cyclotec, Eden Prairie, Minn., U.S.A.) and analyzed for sugars, AIS, starch content, and α- and β-amylase activities.

Moisture content in SPFF was determined by 1st chopping SPFF samples into small chunks and weighing chopped samples before placing them into a convection oven (Precision compact oven; Thermo-Scientific, Waltham, Mass., U.S.A.) to dry at 60 °C until constant weight was obtained. Moisture content was then calculated based on the difference in weight before and after drying SPFF samples. The dried samples were then ground using a Krups F203 electric spice and coffee grinder (Millville, N.J., U.S.A.) for analyses of oil, AIS, starch, and sugar contents in SPFF.

Sugar and AIS contents. Each sample (1 g) was mixed with 25 mL of hot 95% ethanol, vortexed for 1 min, and then centrifuged at 6500 rpm for 10 min. The supernatant was collected in a 50-mL volumetric flask through a filtered funnel and the precipitate was extracted one more time with 25 mL of hot 95% ethanol and centrifuged again at 6500 rpm for 10 min. The obtained supernatants were combined and brought to 50 mL total volume for sugar analysis. The precipitated pellet was air-dried until consistent weight and measured as AIS content. AIS samples were used for starch analysis. Sugar analysis was conducted using a Shimadzu HPLC system (Shimadzu Corp., Kyoto, Japan) equipped with a SIL-20AC HT auto sampler, DGU-20a3 degasser, LC 20AD pump, CTO-20A column oven, and CBM-20A controller. An Antec Leyden model Decade II electrochemical detector in the pulsed mode with a gold electrode was used for detection, and LC Solution software was used for acquisition and quantification. Samples for HPLC analysis were prepared by 1st evaporating ethanol in a SpeedVac system (AES 1010; Savant Instruments Inc., Holbrook, N.Y., U.S.A.) and reconstituted in water at a desired dilution. Glucose, fructose, sucrose, and maltose were separated using a 250 × 4 mm CarboPac-PA1 column attached to a 50 × 4 mm CarboPac guard column (Thermo Scientific, Waltham, Mass., U.S.A.). The eluent was 0.2 N NaOH at a flow rate of 1 mL/min. An external standard curve was used to quantify glucose, fructose, sucrose, and maltose contents. The total sugar content was calculated as the sum of the individual sugars.

Starch content. A Megazyme Assay Kit (K-TSTA) was used according to the manufacturer's directions for total starch determination (Megazyme Intl., County Wicklow, Ireland).

Amylase activities. Alpha-amylase activity was measured using a Megazyme Assay Kit (K-CERA) based on the Ceralpha method. β-Amylase activity was measured using a Megazyme Assay Kit and the βmyl-3 method (K-β3).

Oil content. Approximately 5 g of the oven-dried ground sample was put in a thimble. Oil in the SPFF sample was extracted with hexane for 6 h using a Soxhlet system. The hexane remaining in the flask was evaporated and residual oil was measured as oil content.

Instrumental measurement of texture

The instrumental measurement of texture properties was performed 3 min after the final frying. Sample temperature was at approximately 60 °C. Peak force and overall hardness of SPFF were measured using a TA.XT2*Plus* Texture Analyzer (Texture Technologies Corp., Hamilton, MA, USA) equipped with a 2-mm-cylinder puncture probe (TA-52), and a French fry rig (TA-115W), respectively. Data were collected and analyzed using the Texture Expert software (version 6.1.3.0; Texture Technologies Corp.). For peak force, the velocity of the cylinder probe was set at 3.0 mm/s for pretest and test, and 10 mm/s for posttest. The force was measured using a 5-kg load cell. Peak force was determined as the force (N) required for penetrating the French fry (Walter and others 2002). Four French fries from each batch were used to measure the peak force, and 3 measurements were performed at 3 different locations on each French fry. Twelve different values were collected for one replication. For overall hardness, a 50-kg load cell was used and the velocity of the French Fry Rig test was set at 3.0 mm/s. The area under the curve (AUC) was calculated as overall hardness (N·sec), which represents the energy required for cutting the strips. Five strips were used for each measurement of overall hardness and the measurement was conducted twice for each replication.

Table 3–Sensory attributes with definitions and techniques for evaluation of sweetpotato French fries.

	Attribute	Definition	Technique
Surface texture	Oiliness	Lack of friction on surface	Press sample between thumb and index finger for 3 s (compress sample to 50% of original thickness). Then rub fingers together and evaluate the perception of oiliness.
	Roughness	The perception of deviations in the sample surface often influenced by the overall amount of small and large particles on the surface	Place sample against lips and move sample back and forth across lips. Take note of the perception of deviations in the sample surface.
First bite/chew	Hardness (overall)	Amount of force required to compress the sample	Place sample between back molars and compress sample with molars.
	Fracturability	The degree to which the sample fractures (breaks into distinct pieces)	Observe the sample while bending it to cause a break at the center of the fry. Then place sample between back molars and bite at a fast rate.
	Denseness	Compactness of cross-section	Place sample between back molars and compress sample with molars. Take note of the perception of the amount/thickness of the material in the middle of the French fry that is not air.
Three chew	Crispness (outer)	Multiple, higher-pitched sounds produced as the sample is crushed with the molar teeth	Place sample between back molars and compress sample slowly. Repeat compression 3 times with the same sample.
Initial chewdown	Smoothness (inner)	The degree to which the chewed mass surface/surface of individual particles is smooth	Break the fry in half and bite from the center portion of fry. Evaluate the texture of the inner part of the fry sample by pressing the mass against palate with tongue and ignoring parts of the mass that are from the fry exterior. Evaluate the perception of the surface texture.
	Moistness (inner)	The extent to which the inner section of the fry has a moist or wet texture during mastication	Break the fry in half and bite from the center portion of fry. Evaluate the texture of the inner part of the fry sample by pressing the mass against palate with tongue and ignoring parts of the mass that are from the fry exterior. Evaluate the perceived amount of moisture in the sample.
	Fibrousness (inner)	Amount of stringy fibers perceived in the bolus	Break the fry in half and bite from the center portion of fry. Evaluate the texture of the inner part of the fry sample by pressing the mass against palate with tongue and ignoring parts of the mass that are from the fry exterior. Evaluate the perception of fibers.
Chewdown	Cohesiveness of mass (overall)	The degree to which the chewed sample holds together in a mass	Break the fry in half and bite from the center portion of fry. Chew sample 5 times with molars and use tongue to evaluate the degree to which the pieces of the chewed mass stick to each other.

Sensory analysis

Descriptive sensory analysis (DSA) was conducted to evaluate the sensory textural properties of SPFF. Fourteen panelists consisting of NCSU graduate students, faculty, and staff (12 women and 2 men, ages 21 to 56 y) participated in this study. The sensory panelists were trained on sensory texture attributes of SPFF during 12 different days of 1 h for each training session. The panelists were trained on all attributes using various foods to become familiar with the attributes, followed by training sessions where the panelists practiced scaling attribute intensities with French fries that represented the range of samples in the study. Ten texture attributes, definitions, and evaluation techniques, including those from previous studies of SPFF texture, were slightly modified or further developed by the panel (Table 3). Definitions of oiliness, overall hardness, denseness, inner smoothness, inner moistness, inner fibrousness, and overall cohesiveness of mass were previously described (Truong and others 1997; Walter and others 1997, 2002), and these attribute definitions were modified by the panel in this study. Surface roughness, fracturability, and crispness were described by Meilgaard and others (2015). Evaluation techniques specific for SPFF were developed by the panel for all attributes. The 10 attributes were grouped into 5 categories, which were surface texture (oiliness, roughness), 1st bite/chew (overall hardness, fracturability, and denseness), 3 chew (outer crispness), initial chew down (inner smoothness, inner moistness, and inner fibrousness), and chew down (cohesiveness of mass).

Before conducting DSA for SPFF samples from the 16 genotypes, the performance of each panelist was evaluated, including reproducibility and ability to discriminate between samples. Panelist performance was statistically analyzed using analysis of variance (ANOVA) for each attribute and panelist. Panelists were excluded if scoring was not consistent.

In the sample evaluations, 16 SPFF genotypes were evaluated using a balanced incomplete block (BIB) design for 2 replications (different field plots) of each genotype. Before evaluating products in each session, panelists were calibrated with a commercial frozen SPFF product (Alexia Foods, Long Island, N.Y., U.S.A.) as a reference sample with established attribute intensities that were determined during panel training (Table 4). The reference sample was fried for 150 s at 177 °C, drained, and held for 3 min before evaluation. Experimental SPFF samples were also evaluated 3 min after final frying. Panelists evaluated 4 SPFF samples per session, each coded with a randomly assigned 3-digit code. For descriptive sensory evaluation, a 15-point numerical scale, with 0 = low intensity to 15 = high intensity, was adopted, and each panelist used one score sheet for each sample to avoid bias during evaluations.

Statistical analysis

The experiment was conducted with 2 replications of each genotype, and 2 samples were taken from each replicate for chemical analysis. Randomized order was applied for frying and analyses in all experiments. One-way ANOVA, followed by multiple comparison of means by Tukey's test ($\alpha = 0.05$), was conducted to determine differences among genotypes (SAS software version 9.4, SAS Inst., Inc., Cary, N.C., U.S.A.). For the measurement of peak force, outliers were removed based on the inter-quartile range (IQR) method. Data points more than 1.5 IQR below the 1st quartile or above the 3rd quartile were removed as outliers.

Table 4–Differentiating texture attributes of sweetpotato French fries produced from 16 genotypes.

Genotype	Surface oiliness	Surface roughness	Overall hardness	Fracturability	Denseness	Outer crispness	Inner smoothness	Inner moistness	Inner fibrousness	Cohesiveness of mass
Reference	12.0	11.0	5.5	2.5	7.5	6.5	10.0	8.0	**4.5**	**8.0**
NC08-036	11.3abc	3.8d	1.8g	1.2f	6.0d	0.8e	10.9a	10.0a	2.9^{abc}	7.6^{ab}
Evangeline	10.5abc	5.0abcd	2.1g	1.6ef	5.9d	1.0e	10.7a	9.5ab	3.3^{abc}	8.1^{ab}
NC13-487	11.4abc	4.3cd	9.0a	5.7a	11.0a	2.9cde	7.1c	6.6abc	5.2^{a}	4.1^{c}
NC05-198	12.8a	4.2cd	3.1efg	1.7ef	6.9bcd	1.7cde	9.8a	9.2efgh	4.9^{ab}	7.9^{ab}
Beauregard	10.6abc	4.4bcd	2.8fg	2.0def	5.8d	1.4de	10.4a	7.7bcdef	2.7^{bc}	9.0^{a}
Covington	11.3abc	4.1d	2.8fg	1.1f	6.3d	1.3de	10.7a	8.5abcde	3.5^{abc}	9.2^{a}
NC13-1012	11.8ab	4.9abcd	3.6efg	2.0def	6.6bcd	2.5cde	10.2a	8.8abcd	3.1^{abc}	8.2^{ab}
NC09-122	9.4bcd	4.3cd	3.8defg	2.2def	6.4cd	2.0cde	10.3a	6.7defgh	2.7^{bc}	9.0^{a}
NC13–1001	11.4abc	6.1a	4.9cdef	2.9cdef	6.9bcd	3.8abc	9.6ab	7.9abcdef	3.5^{abc}	9.1^{a}
Porto Rico	10.6abc	5.7abc	4.9cdef	2.8cdef	6.5bcd	3.5bcd	9.5ab	7.2cdefg	3.3^{abc}	8.2^{ab}
Bonita	10.5abc	4.4bcd	5.1cdef	2.7cdef	8.0b	2.6cde	7.2c	5.7fghi	2.0^{c}	7.8^{ab}
NC13–1027	9.3bcd	5.4abcd	6.5bc	3.9bc	7.8bc	4.0abc	7.0c	5.1ghi	3.0^{abc}	7.3^{ab}
NC13–1004	11.2abc	4.5abcd	5.4cde	3.0cde	7.8bc	3.6bcd	7.7bc	5.9fghi	2.0^{c}	8.4^{ab}
NCDM04–197	8.9cd	5.9ab	6.1bcd	3.6bcd	6.4cd	3.6bcd	7.2c	4.6hi	1.9^{c}	7.1^{ab}
Suwon122	7.7de	5.8abc	7.2abc	5.2ab	6.1d	5.5ab	6.3c	4.2ij	1.8^{c}	6.4^{b}
NCDM04-001	5.3e	5.0abcd	8.4ab	6.8a	6.0d	6.1a	3.8d	2.4j	1.6^{c}	3.6^{c}

Values within the column having different inline letters are statistically different ($\alpha = 0.05$).
All attributes were evaluated by DSA panel using a 15-point scale.
Reference is commercial sweetpotato French fries used for calibration of panelists.

For DSA, sample panel means for each attribute were analyzed by ANOVA with means comparison by Tukey's test and principal component analysis (PCA). ANOVA and Tukey's test ($\alpha = 0.05$) were conducted using SAS software to determine differences among genotypes for each sensory attribute. PCA using the correlation matrix was conducted to visualize proximity among genotypes based on overall sensory texture attribute profiles of the samples. PCA was done using XLSTAT 2016 software (Addinsoft, Paris, France). Pearson correlation coefficients were determined for the correlations between chemical, instrumental, and sensory measurements by using SAS 9.4.

Results and Discussion

Chemical components of raw sweetpotato and sweetpotato French fries

Dry matter content. Among the 16 genotypes, DM contents of raw sweetpotatoes were in a wide range of 18.6% to 37.2% (Table 1), which was representative of the 14% to 48% DM range of sweetpotato cultivars reported in previous studies (Brabet and others 1998). NC08-036 had the lowest DM content which was about half of that of NCDM04-001, the genotype with the highest DM content in this study.

As shown in Table 2, moisture content of SPFF ranged from 35.7% to 58.3%. SPFF of all 16 genotypes had lower moisture contents than the original raw sweetpotatoes due to water evaporation during processing such as pre-drying and frying. In general, genotypes with lower DM content in the raw sweetpotatoes tended to have higher moisture content in SPFF. Truong and others (2014) reported that moisture content of Covington SPFF were in the range of 50.1% to 67.7% depending on pretreatments and frying time. The moisture content of 55.5% in the Covington SPFF (Table 2) was in accordance with the previous study.

Sugar content. On a fresh weight basis (fw), glucose, fructose, and sucrose contents of raw sweetpotatoes were 0.05% to 2.26%, 0.03% to 1.43%, and 1.13% to 3.73%, respectively (Figure 1A). Total sugar content (sum of glucose, fructose, and sucrose) in raw sweetpotatoes was 1.22% to 6.49% (Table 1). NC08-036 had the highest and NCDM04-001 had the lowest total sugar content. Total sugar content accounted for 3% to 35% of DM content, and the lower DM genotypes tended to have higher sugar content.

Sugar profiles of SPFF consisted of glucose, fructose, sucrose, and maltose. Total sugar content of SPFF was 0.35% to 10.16% fw (Table 2). Glucose, fructose, sucrose, and maltose contents of SPFF were 0.003% to 3.25%, 0.01% to 2.16%, 0.34% to 4.03%, and 0.00% to 2.53% fw, respectively (Figure 1B). Maltose was not detected in SPFF of NC13-1027 and NCDM04-001, which is consistent with the low β-amylase activity of those genotypes (Table 1). Similar to raw sweetpotatoes, SPFF of NC08-036 had the highest total sugar content and it was about 29 times higher than the product from NCDM04-001, which had the lowest sugar content.

It was expected that sugar content in SPFF would show an apparent increase due to water evaporation during frying. However, the total sugar content of SPFF from NC05-198, NC13-1027, and NCDM04-001 decreased by 3%, 46%, and 71% on a fresh weight basis, respectively (Table 1 and 2). This implied that sugar content changed during processing. Glucose, fructose, and sucrose are water-soluble, so they could diffuse into water during blanching. Conversely, maltose is expected to increase due to hydrolysis of gelatinized starch by β-amylase during heating.

The differences in the contents of maltose and other sugars in raw sweetpotato and fried strips on a dry weight basis (dw) are shown in Figure 2. When considering total sugar content, only NCDM04-197 had an increase of 2.6/100 g dw after processing. The total sugar contents of all other 15 genotypes decreased after processing. Total sugar reduction of Suwon122 was the least (0.1/100 g dw), and that of NC08-036 was the greatest (10.9/100 g dw). Overall, the genotypes with higher total sugar content in raw sweetpotatoes had higher total sugar content after frying. Although sugar reduction by processing was the greatest in NC08-036 on a dry weight basis, this genotype contained the highest total sugar content in SPFF due to higher sugar content in the raw roots and production of maltose during processing.

AIS and starch content. AIS content in raw sweetpotatoes was in a range of 11.6% to 36.7% fw (Table 1). AIS content of raw sweetpotatoes accounted for 62% to 99% of DM content, and the genotypes with high DM content tended to have high

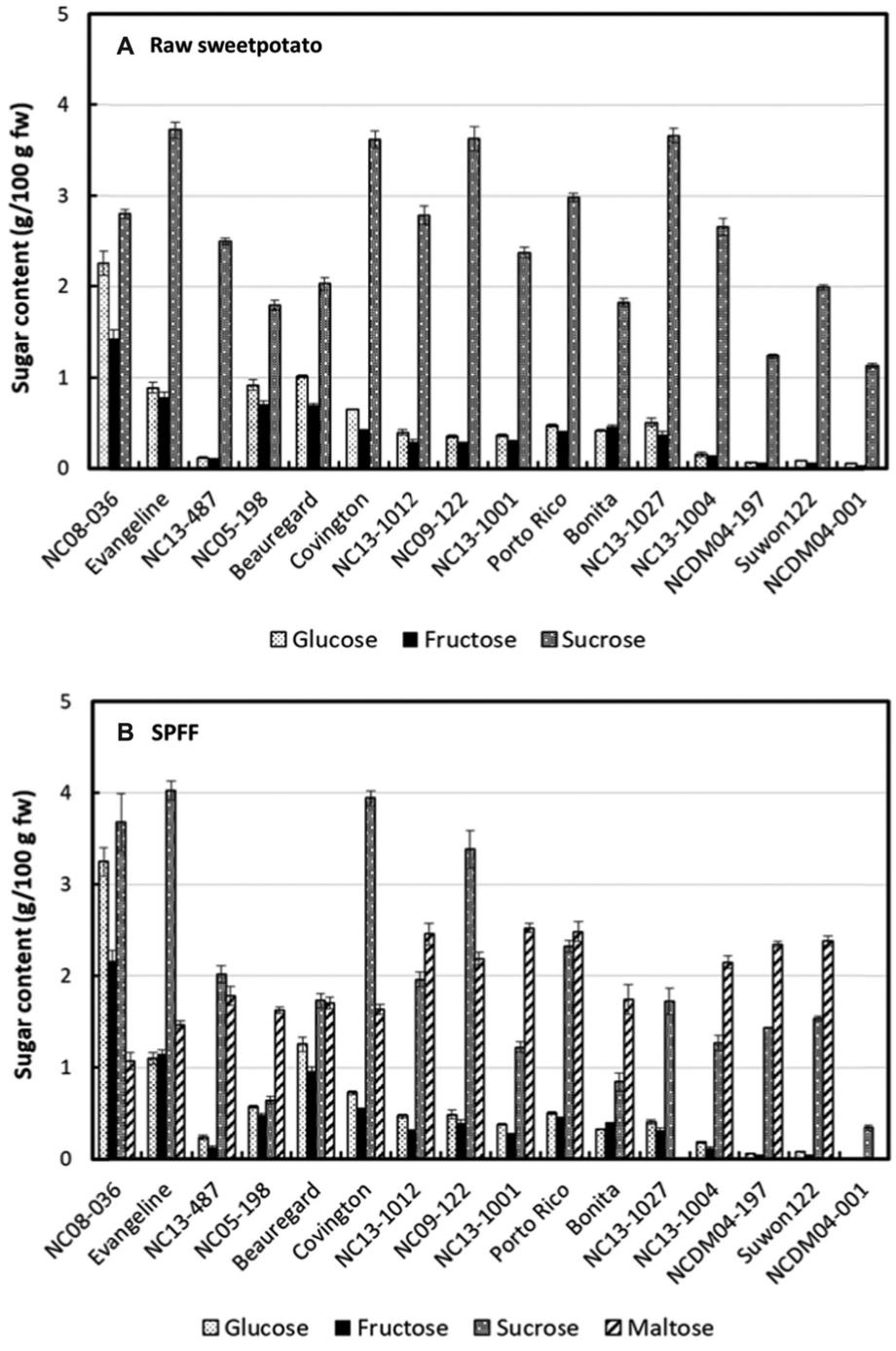

Figure 1–Sugar profiles of raw sweetpotatoes (A) and sweetpotato French fries (B). Error bar indicates standard error.

AIS percentages. Similar to the DM content, NCDM04-001 had the highest AIS content, which was approximately 3 times higher than that of NC08-036. After processing, the AIS content in SPFF increased to 30.8% to 64.2% fw (Table 2) because of moisture evaporation during pre-drying and frying. Similar to the AIS content of raw sweetpotatoes, SPFF from NC08-036 had the lowest AIS content, and SPFF from NCDM04-001 had the highest AIS content.

Starch content of raw sweetpotatoes was in a range of 6.0% to 23.4% fw (Table 1). Starch accounted for 32% to 69% and 52% to 78% of DM content and AIS content, respectively. Genotypes with the higher DM and AIS contents contained more starch. Similar to DM and AIS contents, NC08-036 had the lowest and NCDM04-001 had the highest starch content.

Starch content of SPFF was in a range of 11.6% to 41.4% fw (Table 2). As in the raw sweetpotatoes, SPFF from NC08-036 had the lowest and NCDM04-001 had the highest starch content. Differences in starch content between genotypes were about 17% fw in raw sweetpotatoes and up to 30% fw in SPFF. Therefore, the difference in starch content between raw sweetpotatoes and SPFF samples was compared on a dry weight basis. Starch content decreased by 0.8% to 19.0% after processing and frying. Among

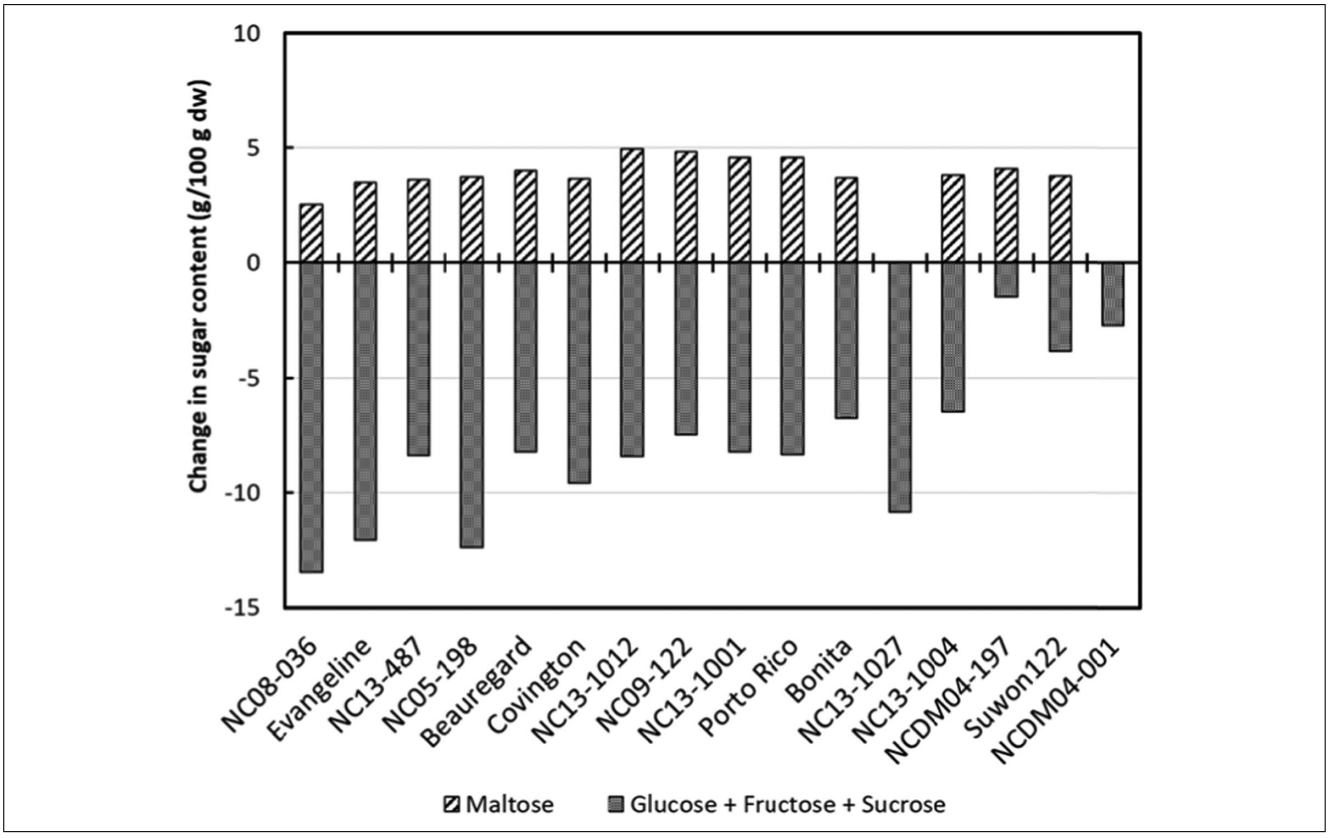

Figure 2–Changes in sugar content in sweetpotato strips after frying. Set initial sugar content as 0 in each genotype. Bar under the zero indicates the amount of decreased sugar after frying. Bar above the 0 indicates the amount of increased sugar after frying.

the 16 genotypes, starch content in SPFF from NC13-1012 and NC13-487 decreased the most, although the decrease in starch in SPFF from NCDM04-001 was much lower than that of the other sweetpotato genotypes. Starch leaks into water during blanching, and the amount of starch leaking could depend on strength of cell structure. Sweetpotato cells can be strengthened by cross-linking between pectin and calcium ion (LaBelle 1971). He and others (2014) reported that the blanching treatment of sweetpotato at 60 °C increased the pectin methylesterase (PME) activity and decreased leaked starch content from 12.83% to 7.28%. Therefore, it is possible that NC13-1012 and NC13-487 had low PME activities or low levels of calcium ion resulting in greater starch reduction. Conversely, it is considered that cells of NCDM04-001 were hardly weakened during blanching and the amount of starch leakage was low. Studies on PME activity and cell structure in tissues of the sweetpotato genotypes are required to provide an understanding on the variation in starch decreases during processing. Other possible reasons for the differences in starch reduction among genotypes could be the initial starch content, amylase activities, and gelatinization temperature. NC08-036 had the lowest starch content, which could result in a smaller amount of starch leaching out.

Amylase activities. α-Amylase activities varied widely among the 16 genotypes (Table 1). Covington had the highest α-amylase activity (130.5 CU/100 g fw), and was twice the 2nd highest genotype, NC13-1001 (63.0 CU/100 g fw). NC13-1027 had the lowest α-amylase activity (12.8 CU/100 g fw).

β-Amylase activity was in a range of 3.9 to 618.9 U/100 g fw and varied widely between genotypes as did α-amylase (Table 1). β-Amylase activity of NC08-036 was the highest, and it was 1.7 times higher than the 2nd highest genotype which was Porto Rico (372.6 U/100 g fw). Among the 16 genotypes, NCDM04-001 and NC13-1027 had very low β-amylase activities, which were 3.9 and 6.0 U/100 g fw, respectively.

β-Amylase has an important role in maltose production. The optimum temperature of sweetpotato β-amylase is 50 °C, and the activity gradually decreases with increasing temperature, until no activity is detected at 80 °C (Tsuyukubo and Ishii 2011). The onset gelatinization temperature of sweetpotato starch from various genotypes is in a range of 66 to 75 °C (Tian and others 1991). As shown in Figure 2, maltose was not detected in the SPFF from NC13-1027 and NCDM04-001, which had low β-amylase activities. However, NC13-1012 had the highest maltose content, even though it had lower β-amylase activity (46.2 U/100 g) than the other genotypes. One possible reason for this phenomenon could be that β-amylase of NC13-1012 was not as readily denatured at the elevated temperatures. Another possible explanation could be that NC13-1012 starch has a lower gelatinization temperature. β-amylase hydrolyzes gelatinized sweetpotato starch, but it is unable to hydrolyze native sweetpotato starch (Ohnishi and others 1985). However, starch content is also important for maltose production as well as β-amylase activity. NC08-036, which had low starch content, contained a smaller amount of maltose, even though it had the highest β-amylase activity among the genotypes. Therefore, a combination of β-amylase activity and its thermal resistance, as well as starch content and gelatinization temperature, could be important for maltose production during sweetpotato processing.

Oil content in SPFF. Oil absorption occurs during frying. Oil content of SPFF was in a range of 6.7% to 12.6% fw (Table 2). The range in oil content of SPFF in our study was

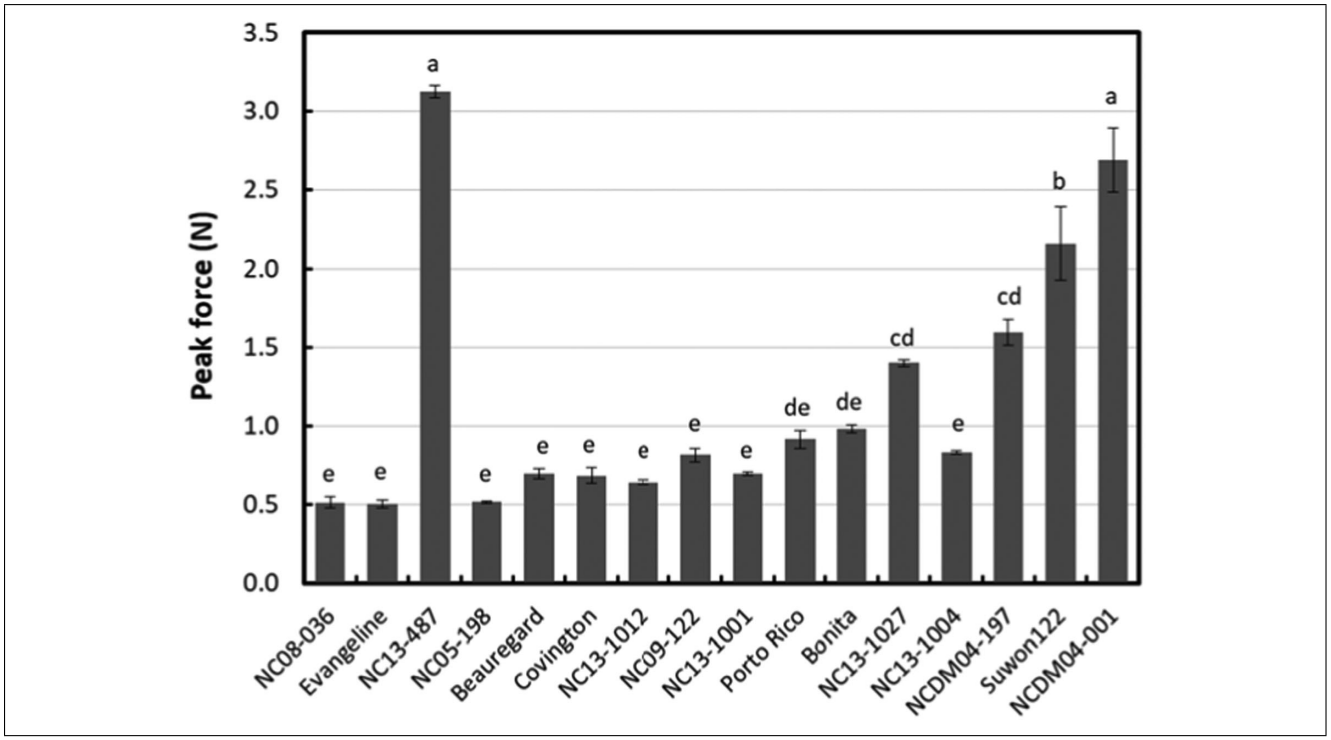

Figure 3–Peak force of sweetpotato French fries. Average peak force. Different letters indicate a significant difference at $P < 0.05$. Error bar indicates standard error; $n = 22–24$.

relatively lower than that of WPFF, which normally ranged from 10% to 15% (Miranda and Aguilera 2006). Among the 16 genotypes, Suwon122 had the highest oil content and Bonita had the lowest.

Instrumental texture measurement

Peak force. Peak force of SPFF from the 16 genotypes was in a range of 0.5 to 3.1 N (Figure 3). SPFF from NC13-487 had the highest and Evangeline had the lowest peak force. Peak force of Evangeline French fries was not statistically different ($P < 0.05$) from 10 other genotypes (NC08-036, NC05-198, Beauregard, Covington, NC13-1012, NC09-122, NC13-1001, Porto Rico, Bonita, NC13-1004). Large distributions of the 22 to 24 individual SPFF peak force values for each genotype (data not shown) could explain the statistical results. Distributions of peak force values of SPFF from NC13-487, Suwon122, and NCDM04-001 were much greater than the other genotypes. Conversely, smaller distributions of peak force were exhibited in the samples from Evangeline and the 10 genotypes with lower peak force mentioned above.

During frying, water in each sweetpotato strip evaporates from the tissue and hot oil comes into the empty space, which results in the crust formation on the surface. Generally, peak force increases with decreases in moisture content. Based on this phenomenon, it is suspected that the variation in peak force among SPFF from the genotypes in this study was likely caused by the difference in the amount of water evaporated from the surface of the strips.

Overall hardness. The overall hardness of the SPFF from the 16 genotypes ranged from 136 to 577 N (Figure 4). SPFF from NCDM04-001 had the highest overall hardness and those of Evangeline had the lowest value. Similar to the result on peak puncture force, no statistically significant difference was found between SPFF from Evangeline and 8 other genotypes (NC08-036, NC05-198, Beauregard, Covington, NC13-1012, NC09-122, NC13-1001, and NC13-1004). High correlation ($r = 0.97$) was found between overall hardness and peak puncture force of SPFF from the 16 genotypes. As with the peak force measurements, measured values of overall hardness were largely dispersed (data not shown).

NC13-487 had unique textural characteristics. After tempering, the strips from NC13-487 were more flexible and elastic as compared to the typical brittleness of the tempered strips from other genotypes (Figure 5). After frying, peak force and overall hardness of SPFF from NC13-487 were very high, although the measured chemical components of this genotype were similar to those of softer genotypes with lower DM content. Cell wall properties and components such as water-soluble pectin could be related to the flexibility of the NC13-487 strips. Previous studies indicated that an increase in water-soluble pectin content in the tissue resulted in the soft texture of cooked vegetables (Fuchigami and others 1993). Regarding the hard texture of SPFF from NC13-487, it is possible that the amount of low-methoxyl pectin in SPFF could affect the hardness. A previous study on pectin using 21 kinds of vegetables found that boiled vegetables with a higher proportion of low-methoxyl pectin were less softened after cooking (Fuchigami 2014). Pectic substances of raw sweetpotatoes and SPFF were not analyzed in our study of 16 genotypes. Further research is required to provide better understanding on the relationship between cell wall components of sweetpotato roots and textural properties of fries.

Sensory evaluation of texture characteristics of sweetpotato French fries

The 16 sweetpotato genotypes produced SPFF with a wide range of sensory texture properties (Table 4). For the relationship among the sensory attributes, overall hardness, fracturability, and outer crispness were highly correlated with each other ($r = 0.84$

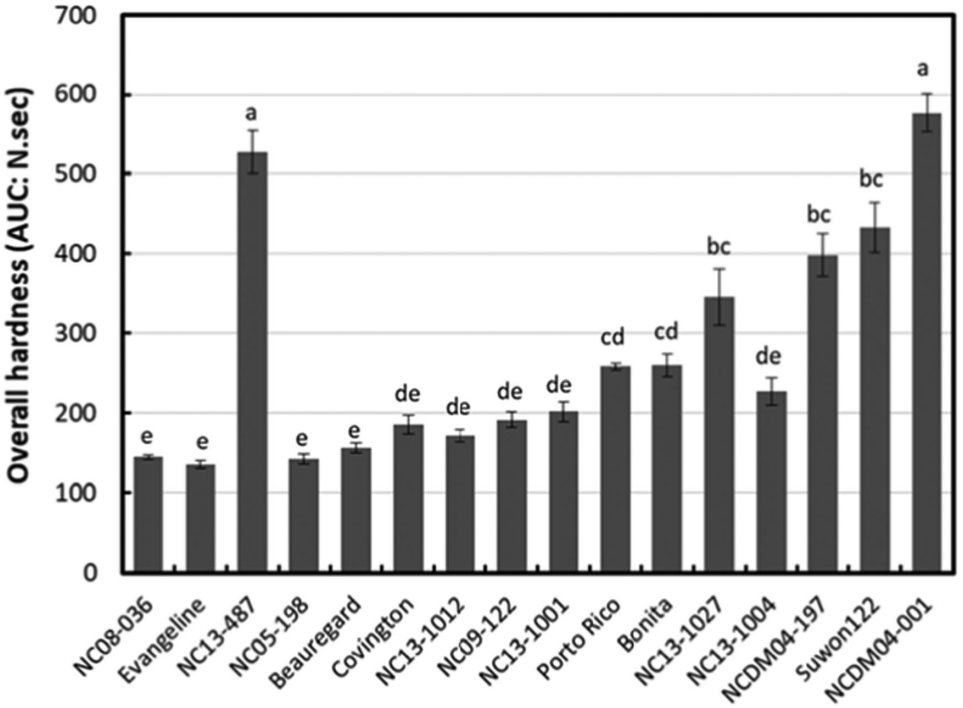

Figure 4–Overall hardness of sweetpotato French fries. Average overall hardness. Different letters indicate a significant difference at $P < 0.05$. Error bar indicates standard error; $n = 4$.

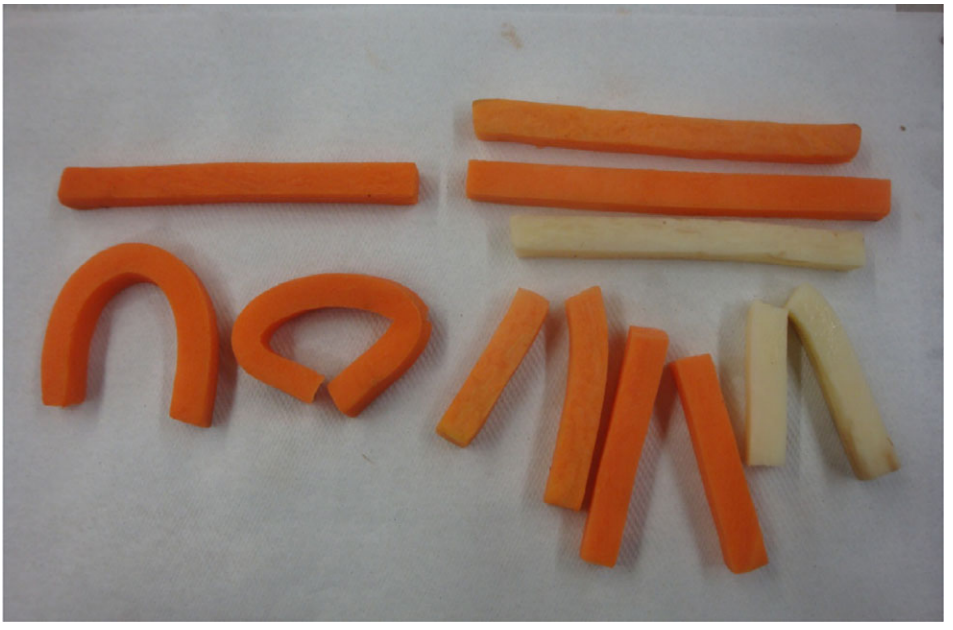

Figure 5–Sweetpotato strips from tempered roots subjected to bending. Flexible strips of NC13–487 (left) and broken strips of NC13-1001, NC05-198, and Bonita (right).

to 0.96), although these attributes were negatively correlated with surface oiliness, inner smoothness, and inner moistness. Surface oiliness, inner smoothness, and inner moistness had positive correlations to each other ($r = 0.74$ to 0.93). High correlation was also found between inner smoothness and cohesiveness of mass. Surface roughness, denseness, and fibrousness were not significantly correlated to any of the other measured sensory attributes.

Figure 6 shows a PCA biplot of the sweetpotato genotypes based on SPFF texture attributes. A total of 83% of variability was explained by principal component (PC) 1 (62%) and PC2 (20.94%). Surface oiliness, inner moistness, inner smoothness, and cohesiveness of mass were positively loaded on PC1, although overall hardness, fracturability, and outer crispness were negatively loaded on PC1. Meanwhile, denseness and fibrousness were positively loaded on PC2.

On the PCA biplot, SPFF of the 8 orange-fleshed genotypes (NC08-036, Evangeline, Beauregard, Covington, NC13-1012, NC09-122, NC13-1001, and Porto Rico) were located close

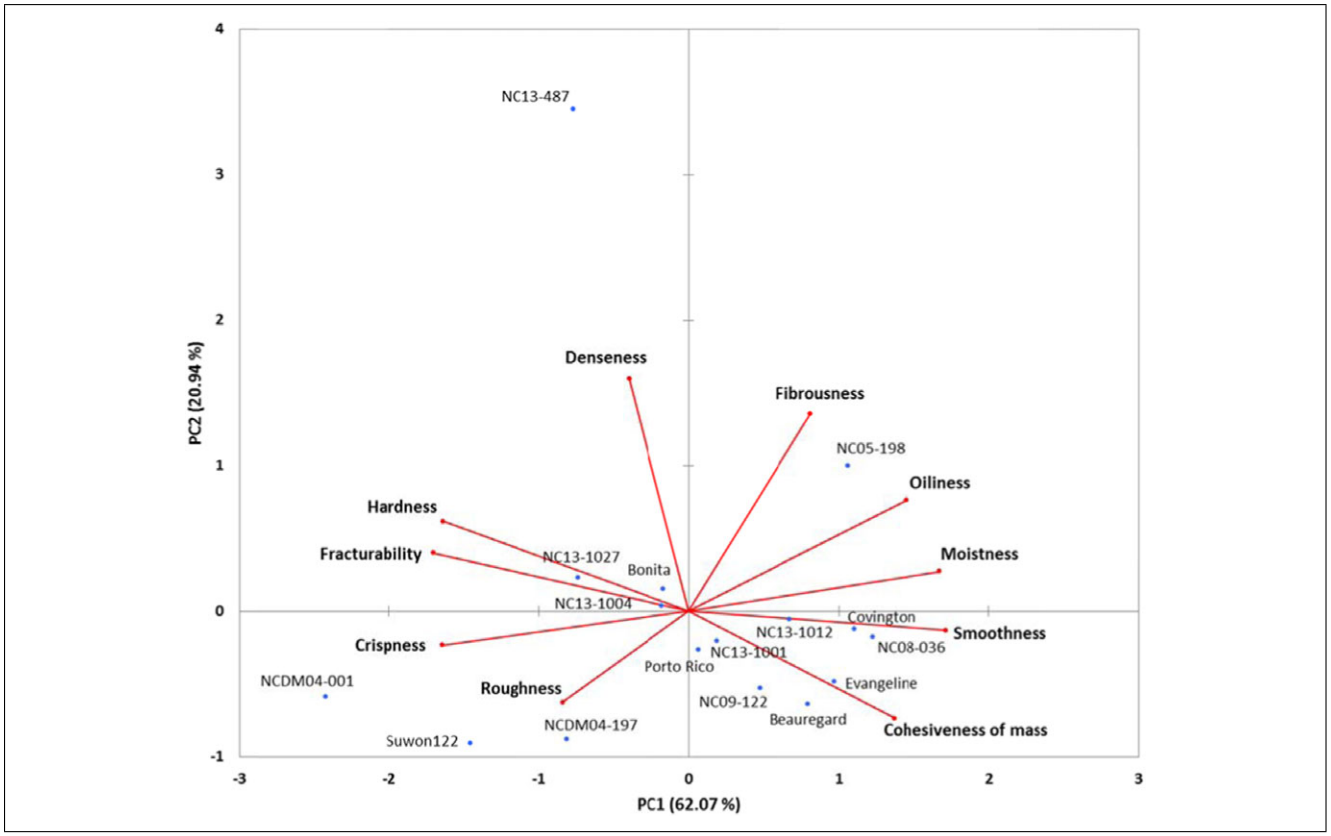

Figure 6–Principal component analysis of sweetpotato French fries accounting for 83% of the variability in all texture attributes.

together. In general, these French fries had more surface oiliness, inner moistness, inner smoothness, and they were more cohesive in texture, and were less hard, less crispy and less easy to be fractured. In addition to these 8 genotypes, NC05-198 SPFF was also loaded on the positive side of PC1 and was characterized by high intensity of fibrousness, as well as oiliness, moistness, smoothness, and cohesiveness of mass. Bonita, NC13-1027, and NC13-1004 were similar to each other and loaded on the negative PC1 and positive PC2 coordinates. They were more dense, less soft, had higher fracturability, were more crispy, and had less inner smoothness and moistness. The 3 yellow-fleshed genotypes (NCDM04-197, Suwon122, and NCDM04-001) had distinct textures, but all 3 were located on the lower left quadrant, negative PC1, and negative PC2 coordinates of the PCA biplot. These SPFF were characterized by crispness, fracturability, hardness, and rough surface texture, and they were not oily, fibrous, or moist. However, the SPFF of NC13-487 was located far from the other genotypes. Sensory characteristics of SPFF from this genotype were completely different from the other genotypes, and it was considered as a unique genotype. This sample was dense, hard, and had high fracturability, fibrousness, and oiliness, although it was not cohesive. Commercial WPFF (Golden Fries Ore-Ida; Kraft Heinz Co., Pittsburgh, Pass., U.S.A.) and SPFF were also evaluated by the DSA panel during training and their sensory characteristics, as compared with those of the 16 genotypes, are shown in Figure 7. The commercial WPFF was crispy and had a rough surface, although it was less oily, less fibrous, drier, and not dense (light, airy interior texture). The commercial WPFF did not group with any of the SPFF from the 16 genotypes, illustrating the unique texture properties of SPFF. The textural characteristics of NC13-1004 and Bonita were similar to commercial SPFF. The SPFF from NC13–1027 grouped in the same quadrant as the commercial, NC13-1004, and Bonita SPFF but were slightly firmer with higher outer crispness and less surface oiliness. Fresh market genotypes like Covington, Evangeline, and Beauregard produced SPFF that were characterized by softer, more moist, smooth, and cohesive textures. Walter and others (1997) reported that consumers dislike a texture of 1st-bite moistness and cohesiveness of mass, suggesting that these commercial sweetpotato varieties may not be ideal for SPFF. However, there is no study reporting the specific SPFF textural characteristics that consumers prefer. In a future study, genotypes from this study exhibiting a wide range of sensory textures could be used to determine the sensory characteristics that drive SPFF consumer preferences.

Relationship between chemical components and instrumental texture measurements

Correlation coefficients between chemical components on a fresh weight basis and instrumental textural values of SPFF processed from the 16 genotypes are shown in Table 5. The DM, AIS, and starch contents in raw sweetpotatoes were positively correlated ($P < 0.01$) with both peak force ($r = 0.41$ to 0.52) and overall hardness ($r = 0.57$ to 0.68). The tendency of the relationship between these 3 chemical measurements and instrumental texture measurement were similar since DM, AIS, and starch contents of raw sweetpotatoes were also positively correlated to each other ($r = 0.73$ to 0.81). Correlation coefficients between starch and AIS contents of SPFF and instrumental texture values of SPFF were increased ($r = 0.51$ to 0.73) compared to those of raw sweetpotatoes. Thus, it is implied that the structure of starch was changed during French fry processing and this change contributed to the hardness of SPFF. Nakamura and others (2010) reported that

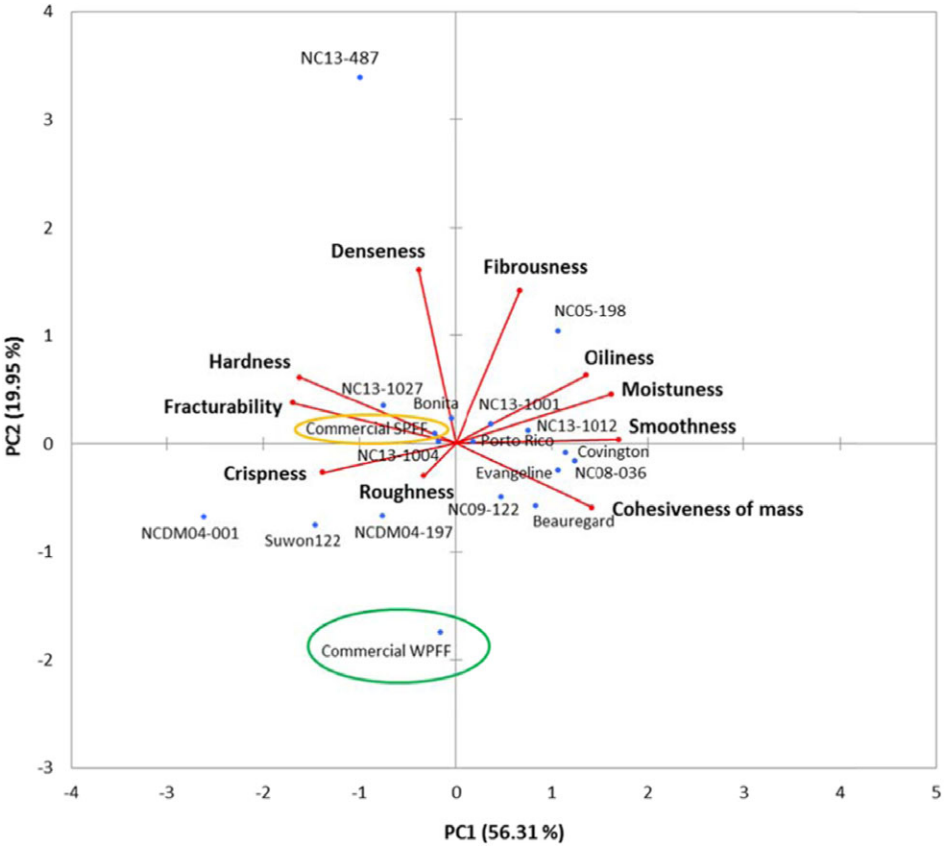

Figure 7–Principle component analysis plot of sweetpotato French fry samples from 16 sweetpotato genotypes as compared with commercial sweetpotato French fries and white potato French fries.

Table 5–Correlation coefficients (*r*) between chemical components and instrumental texture measurement of SPFF from 16 genotypes.

	Peak force		Overall hardness	
	Correlation coefficient	*P*-value	Correlation coefficient	*P*-value
Dry matter (raw)	0.47	<0.0001	0.64	<0.0001
AIS[a] (raw)	0.52	<0.0001	0.68	<0.0001
Starch (raw)	0.41	0.0009	0.57	<0.0001
Total sugar (raw)	− 0.62	<0.0001	− 0.69	<0.0001
α-Amylase activity (raw)	− 0.15	0.1509	− 0.15	0.1585
β-Amylase activity (raw)	− 0.26	0.0245	− 0.30	0.0100
Moisture (fried)	− 0.59	<0.0001	− 0.72	<0.0001
Oil (fried)	− 0.03	0.8276	− 0.01	0.9541
AIS (fried)	0.61	<0.0001	0.73	<0.0001
Starch (fried)	0.51	<0.0001	0.67	<0.0001
Total sugar (fried)	− 0.55	<0.0001	− 0.64	<0.0001

Correlation coefficients were determined on a fresh-weight basis.
[a]AIS, alcohol-insoluble solids.

steamed sweetpotatoes with higher starch content were prone to have a mealy texture, and that starch gelatinization temperature and amylose content were not related to mealy texture. Moreover, a study on WPFF indicated that starch granule size and amylose content had no influence on mealiness of WPFF (Mohr 1972). Starch is gelatinized during processing and forms a gel. In a study on cellular structure of steamed sweetpotato tissue, Nakamura and others (2010) observed that each cell was filled with a starch gel, and maintained its cell structure in the mealy sweetpotatoes, although several cells were combined with starch gel, which leaked from the cells, in the soggy sweetpotatoes. The authors assumed that water molecular motion is limited in the mealy sweetpotatoes as compared to the soggy sweetpotatoes. The moistness of soggy sweetpotatoes can be explained by the water dispersion in the entire structure. Therefore, in our study, it can be expected that the same phenomenon occurred during processing of SPFF, and the difference in the density of gelling starch might affect the texture of SPFF.

Total sugar contents of raw sweetpotatoes and SPFF were negatively correlated with peak force and overall hardness ($r = -0.55$ to -0.69). Sugars have high water-holding capacity and attract water from the surrounding environment. Thus, it is expected that a high sugar content attracts more water, resulting in softer texture of SPFF. However, because DM, AIS, and starch contents were negatively correlated with total sugar content ($r = -0.88$), the effects of these components together with sugar content on the texture of SPFF should be considered. Amylases contribute to starch hydrolysis into maltose during tempering and blanching, but the peak force and overall hardness were not correlated with α-amylase activity ($P > 0.05$). For β-amylase activity, *P*-values were less than 0.05, but correlation coefficients with the peak force and overall hardness were low ($r = -0.26$ to -0.30). In other words, β-amylase activity was related to the hardness of SPFF, but this cannot be used as the sole predictor of hardness.

Moisture content of SPFF was negatively correlated with peak force and overall hardness ($r = -0.59$ to -0.72), which means that moisture content was related to the softer texture of SPFF.

Oil content of SPFF had no correlation with peak force and overall hardness ($P > 0.05$). In contrast, a study on white

Table 6–Correlation coefficients (*r*) between chemical components and descriptive sensory attributes of sweetpotato French fries from 16 genotypes.

	Raw sample						Fried sample				
Attribute	DM[a]	AIS[b]	Starch	Sugar[c]	α-Amylase activity	β-Amylase activity	Oil	Moisture	AIS[b]	Starch	Sugar[c]
Surface oiliness	– 0.77**	– 0.77**	– 0.62*	0.49	0.26	0.37	– 0.15	0.69**	– 0.60*	– 0.77**	0.47
Surface roughness	0.58*	0.56*	0.56*	– 0.45	– 0.13	– 0.17	0.22	– 0.68**	0.63**	0.58*	– 0.36
Overall hardness	0.67**	0.68**	0.67**	– 0.75**	– 0.20	– 0.33	– 0.12	– 0.77**	0.82**	0.69**	– 0.75**
Fracturability	0.68**	0.71**	0.63**	– 0.72**	– 0.25	– 0.33	– 0.04	– 0.79**	0.80**	0.73**	– 0.72**
Denseness	– 0.11	– 0.12	0.02	– 0.21	– 0.10	– 0.04	– 0.46	– 0.01	0.16	– 0.12	– 0.30
Outer crispness	0.90**	0.90**	0.88**	– 0.76**	– 0.14	– 0.41	0.13	– 0.97**	0.97**	0.93**	– 0.77**
Inner smoothness	– 0.81**	– 0.82**	– 0.78**	0.77**	0.24	0.38	0.18	0.80**	– 0.84**	– 0.83**	0.83**
Inner moistness	– 0.90**	– 0.91**	– 0.86**	0.77**	0.25	0.47	0.07	0.82**	– 0.84**	– 0.90**	0.77**
Inner fibrousness	– 0.72**	– 0.71**	– 0.62**	0.33	0.23	0.28	– 0.21	0.52*	– 0.42	– 0.66**	0.21
Cohesiveness of mass	– 0.39	– 0.42	– 0.30	0.51*	0.27	0.09	0.12	0.51*	– 0.51*	– 0.43	0.51*

Correlation coefficients were determined on a fresh-weight basis.
[a]DM, dry matter.
[b]AIS, alcohol-insoluble solids.
[c]Sugar, total sugar.
*$P < 0.05$.
**$P < 0.01$.

potato (WP) crisps, using genotypes with different DM and starch contents, indicated that WP crisps with higher DM content had lower oil content and crispy texture (Kita 2002). The degree of starch gelatinization might be related to oil absorption as observed in WPFF (Pedreschi and others 2016). Moreover, O'Connor and others (2001) reported that the surface layer of WPFF (1 mm) contained a significantly higher amount of oil than the inner part of WPFF. Therefore, in a future study, it is necessary to consider the relationship between oil content and texture of SPFF, based on measuring the oil content of the surface and inner layers separately.

Relationship between sensory texture attributes and chemical components

Several sensory texture attributes of SPFF were correlated with sweetpotato chemical components. Table 6 shows the correlations between sensory attributes and chemical components of raw sweetpotatoes and SPFF. Overall hardness, fracturability, and outer crispness of SPFF increased with increasing DM, AIS, and starch contents in raw sweetpotatoes and SPFF ($r = 0.63$ to 0.97). However, fracturability and outer crispness decreased when moisture and total sugar content increased ($r = –0.72$ to –0.97). Komiyama and others (2002) reported that WPFF with higher starch content was softer and had a more floury texture. In addition, WPFF with 16% starch was preferred by consumers among WPFF processed from raw WP with 12%, 14%, and 16% starch contents in raw WP tubers. Among the 16 genotypes in our study, starch contents from sweetpotato genotypes NC13-1001 and Porto Rico were about 16% in the raw roots. SPFF produced by these sweetpotato genotypes were characterized by high intensities of inner smoothness and cohesiveness of mass and low intensities of denseness, overall hardness, and fracturability. Pavlista and Ojala (1997) reported that raw WP with 21% to 23% DM content had mealy textures and were suitable for WPFF. In our study, sweetpotato genotypes of Beauregard and Covington had 21% to 22% DM. The SPFF produced from these genotypes had soft and moist textures as indicated with higher scores on inner smoothness, inner moistness, and cohesiveness and lower intensities of denseness, overall hardness, and fracturability. Therefore, the differences in starch content and other chemical properties between sweetpotato and WP varieties with similar DM content could have profound effects on the sensory characteristics of French fries.

However, total sugar content in raw sweetpotatoes and SPFF correlated with smooth and moist textures ($r = 0.77$ to 0.83), although increases in DM, AIS, and starch contents were associated with decreasing intensity of these attributes ($r = –0.78$ to –0.91). Sugars have high water-holding capacity and attract water from the surrounding area possibly explaining the positive correlation between total sugar content and sensory inner moistness. The moistness might also affect the smoothness of the SPFF interior. For fibrousness, the DM and AIS contents of raw sweetpotatoes were negatively correlated with sensory fibrousness ($r = –0.71$ to –0.72), although AIS content of SPFF was not significantly correlated ($r = –0.42$). Walter and others (1997) studied the sensory profile of SPFF, and they reported that 1st-bite hardness was negatively correlated with DM content in SPFF ($r = –0.92$), and 1st-bite moistness was highly correlated with sugar and AIS contents of raw sweetpotatoes ($r = 0.94$ to 0.97). The relationships between sugar content and moistness were consistent with the results of our study. However, the sensory perception of texture in relation to DM and AIS contents differed.

Denseness was not correlated with any chemical components of raw sweetpotatoes and SPFF ($P > 0.05$). Surface roughness had a positive correlation with DM, AIS, and starch contents in raw sweetpotatoes and SPFF ($r = 0.56$–0.63, $P < 0.05$), although it was not correlated with total sugar content in raw sweetpotatoes and SPFF ($P > 0.05$). Although correlation was not strong, cohesiveness of mass was positively correlated ($P < 0.05$) with total sugar content in raw sweetpotatoes and SPFF and moisture content in SPFF ($r = 0.51$), and negatively correlated with AIS content in SPFF ($r = –0.51$). The perception of sensory surface oiliness decreased with increasing DM, AIS, and starch contents of raw sweetpotatoes and starch content of SPFF ($r = –0.62$ to –0.77). However, oil content in SPFF and sensory perception of surface oiliness showed no relationship to each other ($P > 0.05$). Oil absorption occurs during frying and the oil penetrates into the crevices where water has evaporated. The movement of oil and water occurs on the surface of strips. The amount of oil absorption of the strip surface layer and inner layer is significantly different, and oil absorption into the outer 1-mm layer is significantly higher than that into the inner core of the strips (O'Connor and others 2001). As well as oil content in SPFF, α- and β-amylase activities

Table 7–Correlation coefficients (*r*) between instrumental measurement and sensory attributes of sweetpotato French fries produced from 16 genotypes.

	Instrumental measurement			
Sensory attribute	Peak force	*P*-value	Overall hardness	*P*-value
Surface oiliness	– 0.61	0.0121	– 0.70	0.0024
Surface roughness	0.21	0.4293	0.33	0.2134
Overall hardness	0.92	<0.0001	0.95	<0.0001
Fracturability	0.94	<0.0001	0.96	<0.0001
Denseness	0.48	0.0573	0.40	0.1256
Outer crispness	0.68	0.0040	0.78	0.0003
Inner smoothness	– 0.82	<0.0001	– 0.90	<0.0001
Inner moistness	– 0.73	0.0013	– 0.83	<0.0001
Inner fibrousness	– 0.06	0.8097	– 0.20	0.4503
Cohesiveness of mass	– 0.91	<0.0001	– 0.89	<0.0001

had no significant correlation with any of the evaluated sensory attributes ($P > 0.05$).

As mentioned above, NC13-487 had a unique texture which affected correlations between chemical components (DM, AIS, starch, and moisture) and sensory attributes, especially overall hardness, and fracturability. Although sensory perceptions of overall hardness, fracturability, and outer crispness were correlated to each other, the correlation of components with outer crispness was not influenced by NC13-487. The SPFF from NC13-487 were hard but not crispy, and the trained sensory panel was able to distinguish this difference. This sample was perceived as having a burnt exterior with an undercooked interior.

Relationship between sensory texture attributes and instrumental measurement

Table 7 shows the correlation coefficient between the instrumental texture values (peak force, overall hardness) and 10 sensory attributes. Sensory overall hardness, fracturability, and outer crispness were positively correlated ($P < 0.05$) with both instrumental values ($r = 0.68$ to 0.96), although surface oiliness, inner smoothness, inner moistness, and cohesiveness of mass had negative correlation with both instrumental values ($r = –0.61$ to $–0.91$). These correlations indicate that instrumental measurement could be used as a tool to narrow the selection of genotypes for SPFF. However, surface roughness, denseness, and inner fibrousness had no significant relationship with the values of instrumental measurements ($P > 0.05$). Walter and others (2002) studied the texture of restructured SPFF, and they reported that instrumental measurements were positively correlated with hardness and density ($r =$ 0.80 to 0.92), and negatively correlated with cohesiveness, oiliness, and moistness ($r = –0.80$ to $–0.91$). Denseness had no significant correlation with the values of the instrumental measurements in our study, although the results of other sensory attributes agreed with the previous study. This could be due to the differences in the product types. In this study, interior denseness could be a function of the genotype rather than a function of formulation, and it could be influenced by variations in compositional differences that do not necessarily correlate with material hardness.

Conclusions

This study demonstrated that sensory texture attributes of SPFF vary widely among sweetpotato genotypes. These variations in texture properties were significantly correlated with chemical components of raw sweetpotatoes and instrumental texture measurements of SPFF. This is the 1st report on sensory texture characteristics of SPFF from a wide range of genotypes evaluated by a trained descriptive analysis panel. Sensory characteristics (overall hardness, fracturability, outer crispness, inner smoothness, and inner moistness) were highly correlated with DM, AIS, starch, and total sugar contents in raw sweetpotato. Therefore, these chemical measurements could be used to evaluate sweetpotato genotypes for processing into SPFF. Because both instrumental texture measurements were highly correlated with each other, only one type of measurement would be needed in a future study. The French fry rig was specifically designed for measuring hardness of French fries and had a slightly higher correlation with the results from sensory evaluation than puncture testing with a 2-mm-cylinder puncture probe. These results would be helpful to plant breeders when developing new sweetpotato varieties suitable for processing into a fried product that meets the increasing consumer demand for high quality SPFF.

Authors' Contributions

A. Sato conducted the experiments, analyzed data, interpreted the results, and drafted the manuscript. V. D. Truong designed the study, supervised the execution of the experiments, assisted in interpretation of the results, and reviewed and revised the manuscript. S. Johanningsmeier collaborated in the study on DSA and reviewed and revised the manuscript. R. Reynolds participated in processing of sweetpotato French fries, chemical analyses, and instrumental texture measurements. K. Pecota and C. Yencho participated in designing the study, selected sweetpotato genotypes with various traits suitable for processing, and they supervised the production and storage of the required root samples for the study.

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