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Relationships between isolated sweetpotato starch properties and textural attributes of sweetpotato French fries

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Abstract: Sweetpotato French fry (SPFF) textures have been associated with dry matter and starch contents, but these do not fully account for all textural differences. This study investigated the relationships between the physicochemical properties of sweetpotato starch and textural attributes of sweetpotato fries. Starches from 16 sweetpotato genotypes that varied in dry matter content were isolated and analyzed. The amylose content, pasting temperatures and viscosities, and textural properties of equilibrated starch gels were measured. Correlational analysis was performed with the respective SPFF mechanical and sensory texture attributes. Sweetpotato starch amylose content ranged from 17.3% to 21.1%, and the pasting and gel textural properties varied significantly between starches. Starch from orange-fleshed sweetpotatoes had lower pasting temperatures than starches from yellow/cream-fleshed genotypes, 72.2 ± 2.0 and 75.5 ± 1.1 °C, respectively. Notable inverse correlations were observed between the starch pasting temperature and perceived moistness ($r = -0.63$) and fibrousness ($r = -0.70$) of fries, whereas SPFF denseness was positively associated with starch pasting viscosity ($r = 0.60$) and nonstarch alcohol-insoluble solids content. Fry textures were likely affected by cooked starch properties, which should be considered when selecting varieties for sweetpotato fries.

Practical Application: Without the aid of a batter, sweetpotato French fries (SPFFs) tend to be soft and limp—undesirable attributes in a fried food. The physiochemical properties of starch, the most abundant component in sweetpotato fries, were further explored in this study to better understand the properties of sweetpotato starch that influence SPFF textures. These findings can be used by sweetpotato processors and breeders for developing new sweetpotato varieties that are designed for production of fried products with desirable textures.

KEYWORDS
French fry, Ipomoea batatas, starch pasting, sweet potato, texture

1 | INTRODUCTION

Sweetpotatoes (*Ipomoea batatas*) are a starchy storage root that is regarded to be the seventh most important crop in the world and produces the most biomass and nutrients per hectare than any other crop (Loebenstein, 2009). Consumption of sweetpotatoes and compounds isolated from sweetpotatoes has been associated with a myriad of health promoting benefits, from antioxidant and anticancer to combating obesity and contributing prebiotics (Albuquerque et al., 2019; Wang et al., 2016). Orange-fleshed sweetpotatoes (OFSP) in particular are an important dietary source of β-carotene and are promoted for combating vitamin A deficiency in vulnerable populations (Truong et al., 2018). The United States' sweetpotato market, primarily made up of OFSP varieties, is steadily growing with the annual production value being more than double that in 2000 and the export market value quadrupling since 2008 (USDA-ERS, 2020; USDA-NASS, 2020).

One of the reasons for this growth is the introduction of a greater range of processed sweetpotato products into the market, including sweetpotato French fries (SPFFs), which has also experienced increased demand (Sato et al., 2018). Current commercial production of sweetpotato fries utilizes sweetpotato varieties that were developed and cultivated for the fresh market, and there is interest in developing new varieties that enhance the quality of processed products. Only a few research studies have investigated the characteristics of fried sweetpotatoes prepared from a variety of genotypes. SPFF textural properties (e.g., hardness, moistness) were associated with sugar, dry matter, starch, and alcohol-insoluble solids contents (Sato et al., 2018; Walter et al., 1997). In sweetpotato chips, the dry matter and starch contents were correlated with the force to break the chip (Gao et al., 2014). However, the effects of the individual constituent's physiochemical properties on the textural properties of fried sweetpotatoes were not explored and is still largely unknown.

Other than water, starch is the predominate component in sweetpotatoes and the content has been associated with textural differences of cooked sweetpotatoes (Kitahara et al., 2017; Yoon et al., 2018). Sweetpotatoes with higher starch contents tend to be dryer and mealier (Kitahara et al., 2017). In addition, sweetpotato starch thermal and viscoelastic properties also vary among genotypes, which is attributed to differences in starch molecular structures (Tong et al., 2020; Zhu & Wang, 2014). Thus, the starch content and starch cooking characteristics could both impact textures of products for human consumption, but little is known on how the thermal and viscoelastic properties of isolated sweetpotato starch relate to perceived textural properties of cooked sweetpotato.

Because starch is a major component of sweetpotatoes, we hypothesized that the isolated sweetpotato starch pasting properties and gel firmness would be associated with the textural properties of SPFFs. Therefore, the objectives of this study were to (1) determine similarities and differences in starch pasting properties and gel texture profiles of a wide range of sweetpotato genotypes and (2) investigate correlations between the sweetpotato starch pasting and gel textural properties and the instrumental and sensory textures of SPFFs.

2 | MATERIALS AND METHODS

2.1 | Raw materials

Sweetpotato starches were isolated from 16 sweetpotato genotypes grown on two independent plots that were used for SPFF production and sensory evaluation by Sato et al. (2018). Sweetpotato genotypes were selected to represent a wide range of dry matter content and sensory textural attributes determined by Sato et al. (2018). All sweetpotatoes were grown at the Horticultural Crops Research Station in Clinton, NC, cured at 85 to 90% RH at 30 °C for 7 days, stored at 80 to 90% RH at 30 °C, and provided by the Sweetpotato Breeding and Genetics Program at North Carolina State University for fry preparation (Sato et al., 2018) and starch extraction. The remaining sweetpotato roots from the two plots used in the SPFF texture study by Sato et al. (2018) were combined and samples were taken for starch extraction following the method described by Walter et al. (2000) with some modifications.

2.2 | Starch isolation

Starch was extracted from the same lots of sweetpotato roots used in the SPFF texture study by Sato et al. (2018). Starch was isolated and retained as separate samples for the two Covington sweetpotato lots that were used in the SPFF texture study. Starch extraction was performed according to the method described by Walter et al. (2000) with some modifications. Briefly, 1-kg batches of washed sweetpotato roots were manually peeled, cut into 3-cm chunks, and blended with 3 L of tap water for 2 min using a heavy-duty blender (model LBC 15, Waring Commercial, Torrington, CT, USA). The slurry was poured through three layers of Miracloth and then allowed to settle for at least 4 hr. The supernatant was discarded, and the sediment suspended again in 3 L of water and allowed to settle for 4 hr. This procedure was repeated two additional times. After the final decantation, the top colored layer of starch was scraped off and discarded. The isolated starch was allowed to air-dry (22 °C) for 2 to 3 days and stored at 4 °C.

2.3 | Starch pasting properties

Sweetpotato pasting properties were analyzed by a Rapid Visco Analyzer (RVA) model Super 4 (Perten Instruments, Springfield, IL, USA) using 2.25 g of starch in 22.75 ml of water (9% w/w starch slurry). The RVA heating profile was 50 °C hold for 1 min, heated to 95 °C at 12 °C/min, 95 °C hold for 2.5 min, cooled to 50 °C at 12 °C/min, and finished with a 50 °C hold for 2 min. The mixing rate was 960 rpm for the first 10 s followed by 160 rpm for the remainder of the test. Pasting profiles were generated in at least triplicate for each sweetpotato starch. The pasting temperature, peak time (converted to peak temperature), and the peak, trough, breakdown, final, and setback viscosities were recorded.

2.4 | Instrumental texture profile analysis

Following RVA analysis, each starch paste was transferred into two 10-ml glass beakers (diameter 22 mm) to a height of 15 mm, then stored at 4 °C for 48 hr to promote gel formation for a total of six gels for each starch (Figure S1). Gels were removed from the glass beakers, and the instrumental texture profiles of the starch gels were analyzed using a Stable Micro Systems (Godalming, UK) TA-XT Plus Texture Analyzer with a 50-mm cylindrical probe at a speed of 1 mm/s to 50% deformation and a 5 s hold between duplicate compressions. Texture profile parameters measured were *hardness*: peak force of the first compression; *cohesiveness*: the ratio of the second compression force peak area (work) to the first compression force peak area; *adhesiveness*: the area of the negative work between the first and second compression; and *gumminess*: hardness multiplied by cohesiveness (Friedman et al., 1963). Some of the 9% w/w starch gels were fragile and sample handling for texture profile analysis may have contributed to some of the variability observed (Table 2).

2.5 | Amylose content

Amylose contents of sweetpotato starches were measured using a Megazyme (Bray, Ireland) Amylose/Amylopectin Enzymatic Assay kit following the manufacturer's assay procedure. Briefly, the native starch was gelatinized in 100 °C dimethyl sulfoxide (DMSO), then precipitated using ethanol to separate the starch from lipids and free sugars. The precipitated starch was redissolved in DMSO, then Concanavalin A (a lectin) was added to precipitate amylopectin, the amylopectin-Concanavalin A complex was discarded, whereas the dissolved amylose was fully hydrolyzed into D-glucose using a mixture of α-amylase and amyloglucosidase. The D-glucose from amylose was converted to quinoneimine using the GOPOD reagent (glucose oxidase, peroxidase, 4-aminoantipyrine, and *p*-hydroxybenzoic acid) and quantified by absorbance at 510 nm using a Varian spectrophotometer, Cary WinUV model 300 (Palo Alto, CA, USA).

2.6 | SPFF textures: Sensory attributes and instrumental texture measurements

Sweetpotato starches characterized in this study were isolated from the same sweetpotatoes used for preparation and evaluation of SPFF textures in Sato et al. (2018). SPFF texture was determined by a trained sensory analysis panel and instrumental analyses. The methods are reported in detail in Sato et al. (2018) and the data were incorporated into the correlational and multivariate models in this study to delineate the role of individual starch characteristics in the context of the known influence of dry matter content and other compositional variables. Briefly, SPFF texture attributes (Table S1) were scored by a trained, 14-member descriptive sensory analysis panel using intensity scales that ranged from 0 to 15 that were calibrated with a commercial SPFF reference sample. Samples were coded, fried in a randomized incomplete block design, and presented warm (3 min after frying, ~60 °C) for independent evaluation by each panelist. All experimental protocols were conducted in a food-grade environment using hygienic practices and following all guidance for use of human subjects outlined by the Institutional Review Board at North Carolina State University (Raleigh, NC, USA). Instrumental texture analyses were performed on the same batch of fries evaluated by the sensory panel, including peak puncture force with a 2-mm cylindrical puncture probe and overall hardness determination with a French fry rig (Texture Technologies Corp., Hamilton, MA, USA). Sensory attribute panel means and average instrumental texture values for each genotype and lot were used for the statistical analyses in this study.

2.7 | Data analysis

Isolated sweetpotato starch characteristics were correlated with the corresponding SPFF textural properties reported in Sato et al. (2018). Generation of graphs and tables, Pearson's correlation coefficients (r), and significance of

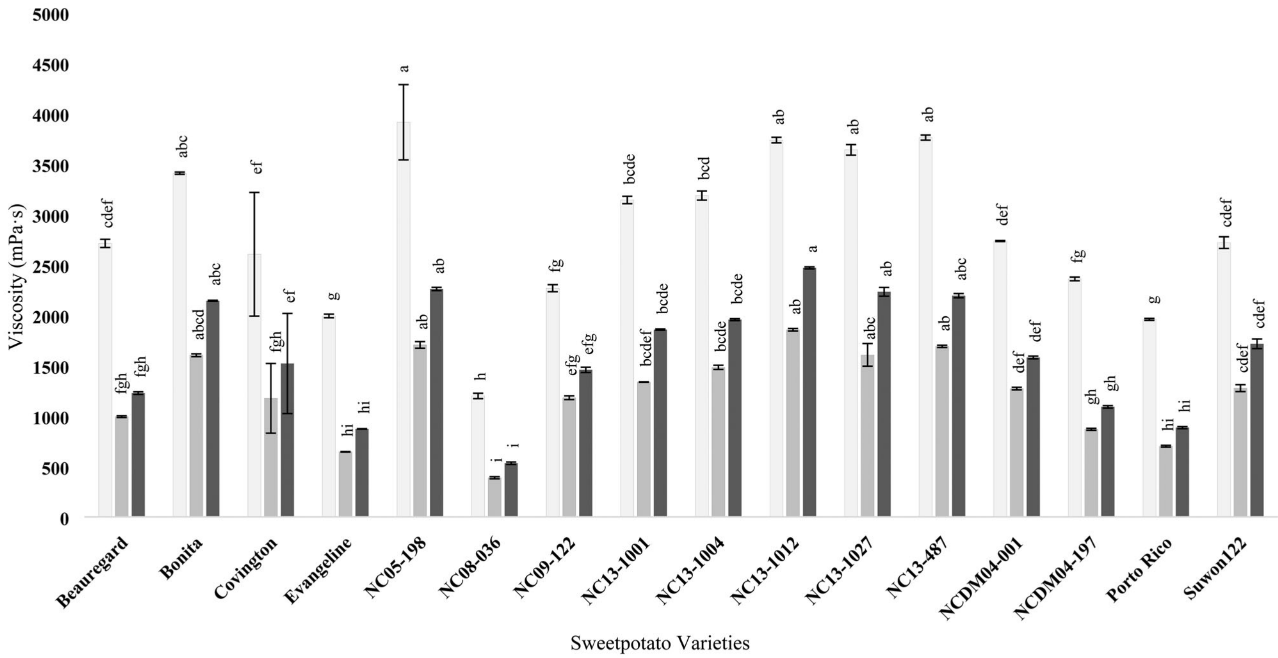

FIGURE 1 Pasting peak (white), trough (light gray), and final (dark gray) viscosities of 9% w/w sweetpotato starch slurries. Error bars represent 1 standard deviation. Statistical groupings within peak, trough, and final viscosities are indicated by lowercase letters ($\alpha = 0.05$)

correlations were performed using Microsoft Excel 365 (Redmond, WA, USA). The *p*-values of correlations were calculated using a two-tailed Student's *t*-test. Data distribution plots of significant starch properties to SPFF texture correlations (Figures S19–S31) and confirmation of correlation analysis were conducted in JMP Pro 14.2.0 (SAS Inc., Cary, NC, USA) using the Liner Fit function of a Fit Y by X scatterplot. Differences in amylose contents, pasting properties, and gel textural properties between sweetpotato starches were compared using one-way ANOVA followed by Tukey HSD post- hoc tests ($\alpha = 0.05$) in JMP Pro 14.2.0. The differences in the starch pasting and gel textural properties from OFSP and yellow/cream/white-fleshed sweetpotatoes were compared using Student's *t*-tests ($\alpha = 0.05$) also in JMP Pro 14.2.0. Partial least squares (PLS) analyses were used to model measured starch properties and raw sweetpotato and SPFF compositions (effects) on the SPFF textures (responses). A *K*-fold cross validation ($K = 7$-fold) using the nonlinear iterative PLS method was used to select the optimum number of latent factors in the PLS model. PLS modeling of the effects (starch properties and compositions) to the individual SPFF textures was also performed and variables with a variable importance in projection (VIP) score greater than 1.0 were considered strong predictors. PLS modeling was performed in JMP Pro 14.2.0.

3 | RESULTS AND DISCUSSION

3.1 | Isolated sweetpotato starch properties

3.1.1 | Starch pasting properties

The pasting properties of the 16 sweetpotato starches varied significantly but were comparable to those of African (Tsakama. et al., 2010) and New Zealand (Cui & Zhu, 2019) sweetpotato starches. Peak viscosities ranged from 1199 to 3912 mPa·s, trough viscosities from 388 to 1606 mPa·s, breakdowns from 811 to 2070 mPa·s, final viscosities from 532 to 2468 mPa·s, and setbacks from 144 to 625 mPa·s (Figures 1, 2, and S2–S17, and Table S2). By far, NC08-036 starch had the lowest pasting viscosities (peak, trough, and final), whereas Evangeline, NC09-122, NCDM04-197, and Porto Rico starches were in the next lowest pasting viscosities group (Figure 1 and Table S2). The starches with the highest pasting, trough, and final viscosities were from Bonita, NC05-198, NC13-1012, NC13-1027, and NC13-487 sweetpotatoes (Figure 1 and Table S2). It is important to note that the pasting viscosities were positively correlated with one another (Table 1), suggesting paste profiles with high peak viscosities will also have higher trough and final

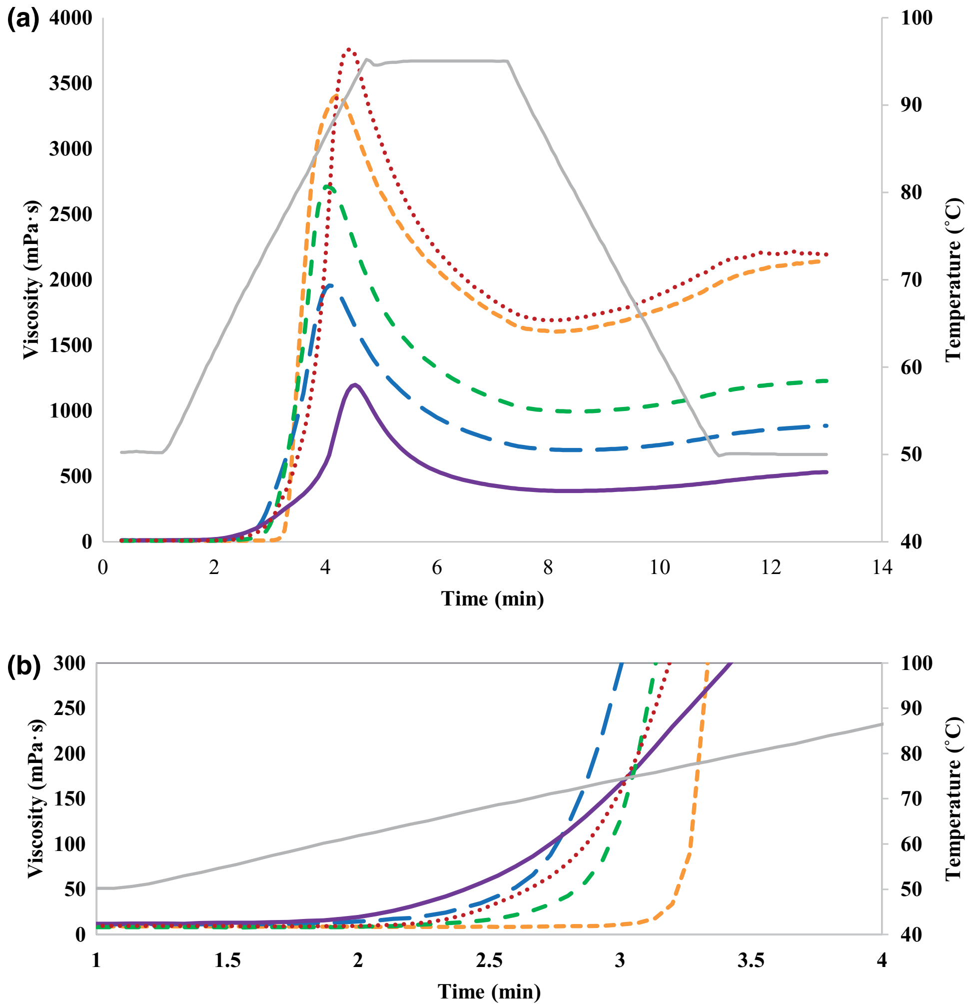

FIGURE 2 Rapid Visco Analyzer pasting profiles (a) and pasting onsets (b) of NC08-036 (purple, solid line), Porto Rico (blue, long dash line), Beauregard (green, medium dash line), Bonita (yellow, short dash line), and NC13-487 (red, dotted line) sweetpotato starches. Error bars represent 1 standard deviation and the gray line is the RVA chamber temperature

viscosities. Similar correlations among pasting viscosities of sweetpotato starches were reported by Collado et al. (1999) and Tsakama et al. (2010). There were also positive correlations between the peak, trough, and final viscosities with the breakdown and setback viscosities (Table 1); thus, the starches with greater thickening power had the biggest changes in viscosity during the pasting profile.

The pasting temperatures and peak viscosity temperatures also varied significantly between sweetpotato starches. Pasting temperatures ranged from 69.3 to 76.7 °C, which is similar to the 70.2 to 76.6 °C range ($n = 106$) reported by the International Potato Center (CIP) (Brabet et al., 1999); and peak temperatures ranged from 86.3 to 92.7 °C (Figure 3). Despite the pasting temperature preceding the peak temperature, the pasting temperatures and peak temperatures were not correlated to one another (Table 1), suggesting that the granule swelling rates and granule integrities (resistance to rupturing) were independent of the pasting temperature. For example, starches with greater amounts of short amylopectin chains (DP 6–12) tend to have lower pasting temperatures (Tong et al., 2020), whereas the peak pasting temperature (or peak time) is a function of granule swelling rates and swollen granule integrities. Granule swelling is affected by the amylose and lipids, which restrict swelling (Tester & Morrison, 1990), whereas the integrities of swollen granules increase with amylopectin–amylopectin entanglement (Han & Hamaker, 2001; Vamadevan & Bertoft, 2020). Albeit the pasting temperature must precede the peak temperature, these temperatures are independent of each other due to the different factors affecting them.

When starch pasting properties were grouped by sweetpotato flesh color, orange or yellow/cream (Table S3), the pasting temperature was the sole significantly different pasting property. The pasting temperatures of starches isolated from OFSP (72.2 ± 2.0 °C) were lower than the

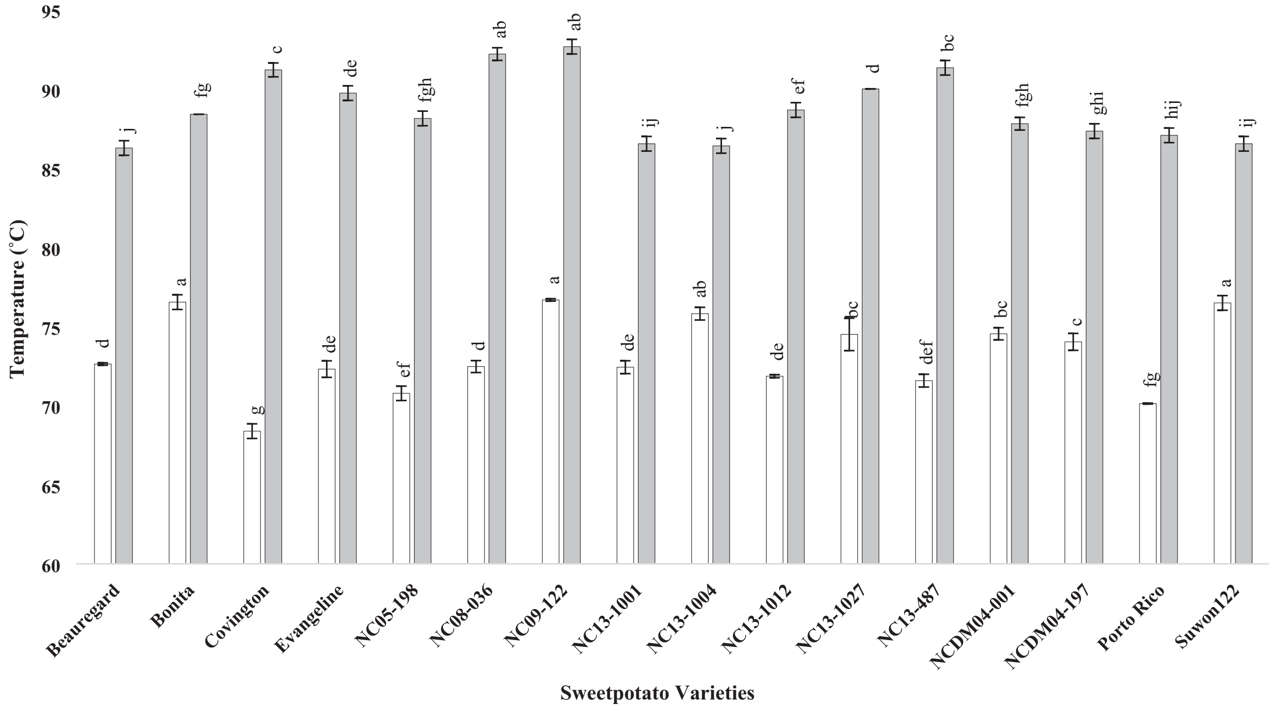

FIGURE 3 Pasting temperatures (white) and peak temperatures (gray) of 9% w/w sweetpotato starch slurries. Error bars represent 1 standard deviation. Statistical groupings within pasting and peak temperatures are indicated by lowercase letters ($\alpha = 0.05$)

starches isolated from yellow/cream-fleshed sweetpotatoes (75.5 ± 1.1 °C) (Figure 4a). Similarly, when the pasting temperatures reported in Waramboi et al. (2011), Yoon et al. (2018), and Lee and Lee (2017) were analyzed by flesh color (combined with this study's data and separately), again, the starch from OFSP was lower than yellow/cream/white-fleshed sweetpotatoes (Figures 4b and 4c). This difference in pasting temperatures may be due to biochemical differences in OFSP versus yellow/cream/white-fleshed sweetpotatoes. OFSP have much higher carotenoid levels (mostly β-carotene) (Donado-Pestana et al., 2012; Truong et al., 2018), which are negatively associated with dry solid and starch contents (Cervantes-Flores et al., 2011; Noda et al., 1998; Tomlins et al., 2012). Both starch and carotenoids are energy sinks (Cazzonelli, 2011); therefore, the energy demand to produce carotenoids may be impacting the starch granule architecture in a manner that results in a lower pasting temperature. Lee and Lee (2017) also reported an OFSP starch (undisclosed variety) had a lower pasting temperature than starch from a white-fleshed variety (undisclosed variety) and attributed it to the starch swelling more rapidly after gelatinization. Interestingly, the gelatinization temperatures reported in Waramboi et al. (2011) were not significantly different between OFSP and yellow/cream/white-fleshed sweetpotatoes (Figure S18). Thus, the gelatinization temperature is not the sole factor influencing the pasting temperature. It is unclear why starches from OFSP paste at lower temperatures and swell faster.

Starch pasting properties are affected by multiple variables, such as amylose contents (Tester & Morrison, 1990), amylose lengths and amylopectin molecular weights (Mua & Jackson, 1997), positioning of amylose within the starch granule (Vamadevan & Bertoft, 2020), amylopectin molecular structures (Han & Hamaker, 2001; Tong et al., 2020; Zhu et al., 2011), granule proteins and lipids (Debet & Gidley, 2006), phosphorus content (Abegunde et al., 2013), and granule size (Chen et al., 2003). Therefore, the effects of starch structure on pasting profiles are complex (Jane et al., 1999) and not yet fully elucidated for sweetpotato. Nonetheless, significant variation in pasting profiles of sweetpotato starches demonstrated the potential effects of starch structure on the varying textures of processed sweetpotatoes.

3.1.2 | Starch gel textural properties

The textural properties of the sweetpotato starch gels also varied significantly among the genotypes (Table 2) regardless of the flesh color. Gel hardness values ranged from 172 to 922 g, adhesiveness from ≈0 to −39.2 g·s, cohesiveness from 0.34 to 0.86%, and gumminess from 138.7 to 728.6 g (Table 2). Evangeline, NC09-122, NCDM04-197, and

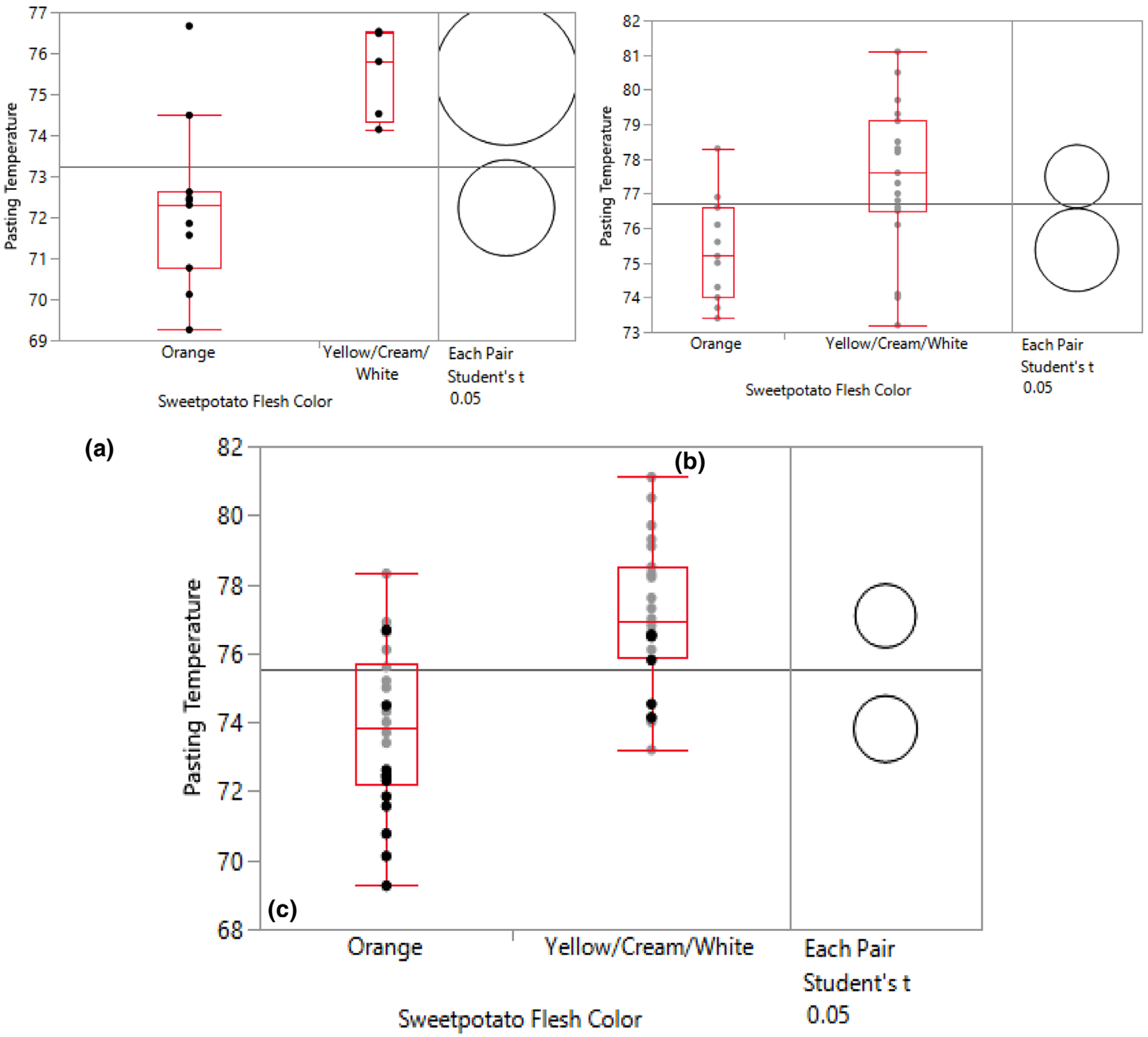

FIGURE 4 Student's *t*-tests ($\alpha = 0.05$) and quantiles of sweetpotato starch pasting temperature averages grouped by sweetpotato flesh color from this study (a); Yoon et al. (2018), Waramboi et al. (2011), and Lee and Lee (2017) (b); and combined data from this study (black dots) and the other studies (gray dots) (c). *Reported pasting temperatures of sweetpotatoes with purple flesh or unidentified flesh color were not included

Porto Rico starch gels were the hardest and most gummy, whereas Bonita, NC05-198, NC13-1001, NC13-1004, NC13-1012, NC13-1027, and NC13-487 starch gels were the least hard and gummy (Table 2). In general, starch gels with greater hardness and gumminess values also tended to have greater adhesiveness (greater adhesiveness is represented by more negative values) (Table 1). However, it is important to consider that adhesiveness is considered as a "secondary parameter" by the TPA instrument manufacturer due to risk of erroneous measurements from the sample sticking to the probe (Texture Technologies, 2015). Several coefficients of variation for adhesiveness (Table 1) were exceptionally high; thus, no clear conclusions can be drawn with regard to starch gel adhesiveness. Most starch gels had similar cohesiveness values around 0.75% to 0.85%, but the NC08-036 starch gels had exceptionally low cohesiveness (0.34%), suggesting the gel was fragile and substantially compromised after the first compression.

The starch gel hardness values were negatively correlated with the RVA pasting viscosities (Table 1); therefore, starches with lower pasting viscosities solidified into harder gels. The gel hardness was not simply due to a greater final viscosity, rather the differences in starch gel hardness values were likely a result of varying extents of retrogradation. Ishiguro et al. (2000) also reported textural differences of sweetpotato starch gels and demonstrated

TABLE 1 Pearson correlation coefficients (*r*) between sweetpotato starch amylose percentages (bolded), Rapid Visco Analyzer measured properties, and Texture Analyzer measured properties (italicized) (***P*-value <0.01; **P*-value <0.05)

	Amylose	**Pasting temp.**	**Peak viscosity**	**Peak temp.**	**Trough viscosity**	**Breakdown**	**Final viscosity**	**Setback**	***Hardness***	***Adhesive-ness***	***Cohesive-ness***
Pasting temp.	−0.03										
Peak viscosity	−0.62*	−0.03									
Peak temp.	−0.35	−0.12	−0.22								
Trough viscosity	−0.56*	0.16	−0.96**	−0.12							
Breakdown	−0.63**	−0.11	−0.96**	−0.31	−0.84**						
Final viscosity	−0.55*	−0.15	−0.97**	−0.12	−0.99**	−0.85**					
Setback	−0.48	−0.13	−0.92**	−0.13	−0.93**	−0.84**	−0.96**				
Hardness	−0.45	−0.01	−0.87**	−0.16	−0.84**	−0.84**	−0.87**	−0.91**			
Adhesiveness	−0.24	−0.15	−0.75**	−0.12	−0.68**	−0.76**	−0.72**	−0.82**	−0.86**		
Cohesiveness	−0.53*	−0.19	−0.70**	−0.50*	−0.68**	−0.67**	−0.66**	−0.56*	−0.37	−0.24	
Gumminess	−0.28	−0.08	−0.68**	−0.03	−0.65**	−0.65**	−0.69**	−0.77**	−0.94**	−0.84**	−0.02

the gel firmness was associated with retrogradation. It is postulated that the sweetpotato starch gels with lower hardness values (Table 2) retrograded less, possibly due to differences in the amylopectin structures. The amylopectin structure affects the retrogradation attributes, where amylopectin molecules with greater amounts of short A-chains (DP 6–12) tend to retrograde less (Vamadevan & Bertoft, 2018). In addition, these short A-chains have been positively correlated with higher pasting peak viscosities of sweetpotato starches (Tong et al., 2020; Zhu et al., 2011), which is consistent with the pasting peak viscosities negatively correlated with gel hardness in this study (Table 1). Therefore, it was likely that the sweetpotato starches with greater amounts of short A-chains resulted in high pasting peak viscosities and weak starch gels. For example, we hypothesize that NC05-198 starch likely had a higher ratio of short A-chains because it had a high pasting viscosity (Figures 1 and S6 and Table S2) and low gel hardness value (Table 2).

3.1.3 | Amylose content of sweetpotato starches

Sweetpotato starch amylose content ranged from 17.3% to 21.1% (Table 2). These were similar to previous reports, which ranged from 18.63% to 20.45% (Tong et al., 2020) and 18.6% to 27.1% with more than half of the evaluated CIP sweetpotatoes being within 20%–23% amylose (Brabet et al., 1999). Despite the narrow amylose percentage range, there were significant negative correlations with the pasting viscosities and the cohesiveness of the starch gels (Table 1), suggesting that small differences in amylose content may partially contribute to the sweetpotato starch pasting and gelling properties. During pasting, amylose restricts granule swelling (Tester & Morrison, 1990) and contributes minimal viscosity to the hot paste (trough viscosity) (Mua & Jackson, 1997). Thus, greater amounts of amylose in sweetpotato starch likely acted as an antagonist to granule swelling while not substantially contributing to the overall viscosity, resulting in lower pasting viscosities. Upon cooling, amylose begins to associate causing an increase in setback viscosity and greater setbacks are experienced with larger amylose molecules (Mua & Jackson, 1997). As the amylose–amylose interactions continue to increase with time, the cohesiveness of amylose gels also continues to decrease (Mua & Jackson, 1997). The relatively high amylose percentage of NC08-036 starch (Table 2) could be partly contributing to the exceptionally low peak pasting viscosity (Figures 1 and S7) and low gel cohesiveness (Table 2). However, it is important to note that the impact of amylose on pasting and gelling properties is not solely based on content but on amylose

TABLE 2 Sweetpotato starch gel textural properties and amylose contents. Statistical groupings within texture analyzer properties and amylose contents (columns) are indicated by lowercase letters ($\alpha = 0.05$)

	Texture analyzer properties				
Variety	**Hardness (g)**	**Adhesiveness (g·s)**	**Cohesiveness (%)**	**Gumminess (g)**	**% Amylose**
Beauregard	594 ± 89^{de}	-23.77 ± 20.47^{abc}	0.81 ± 0.02^{ab}	482.4 ± 74.2^{bcd}	17.8 ± 0.6^{ab}
Bonita	252 ± 16^{f}	-7.46 ± 1.62^{a}	0.85 ± 0.01^{ab}	213.4 ± 14.5^{e}	17.7 ± 0.5^{ab}
Covington	631 ± 320^{cde}	-14.15 ± 13.18^{ab}	0.78 ± 0.09^{ab}	471.1 ± 215.6^{cd}	18.7 ± 1.9^{ab}
Evangeline	824 ± 63^{abcd}	-24.09 ± 14.6^{abc}	0.78 ± 0.06^{ab}	645.1 ± 71.3^{abc}	21.1 ± 1.2^{ab}
NC05-198	171 ± 19^{f}	-0.63 ± 0.41^{a}	0.84 ± 0.01^{ab}	143.4 ± 16.2^{e}	17.3 ± 1.0^{b}
NC08-036	672 ± 72^{bcde}	-20.8 ± 14.3^{abc}	0.34 ± 0.13^{c}	228.8 ± 85.3^{e}	21.0 ± 0.3^{a}
NC09-122	881 ± 38^{ab}	-43.24 ± 9.83^{c}	0.75 ± 0.04^{b}	662.6 ± 59.7^{ab}	18.9 ± 1.4^{ab}
NC13-1001	200 ± 9^{f}	-1.57 ± 1.27^{a}	0.79 ± 0.02^{ab}	158.2 ± 5.2^{e}	17.6 ± 0.8^{ab}
NC13-1004	255 ± 23^{f}	-6.49 ± 3.76^{a}	0.85 ± 0.02^{ab}	217.4 ± 17.2^{e}	19.7 ± 2.5^{ab}
NC13-1012	163 ± 8^{f}	-0.15 ± 0.16^{a}	0.86 ± 0.02^{ab}	140.1 ± 6.7^{e}	19.4 ± 0.7^{ab}
NC13-1027	175 ± 13^{f}	-4.3 ± 9.41^{a}	0.83 ± 0.03^{ab}	145.4 ± 11.7^{e}	18.1 ± 0.4^{ab}
NC13-487	172 ± 11^{f}	-0.86 ± 0.92^{a}	0.81 ± 0.02^{ab}	138.7 ± 6^{e}	19.0 ± 0.7^{ab}
NCDM04-001	523 ± 67^{e}	-34.1 ± 15.84^{bc}	0.87 ± 0.02^{a}	454.2 ± 60.5^{d}	18.5 ± 0.8^{ab}
NCDM04-197	922 ± 160^{a}	-21.67 ± 16.81^{abc}	0.78 ± 0.09^{ab}	728.6 ± 183.5^{a}	19.2 ± 1.7^{ab}
Porto Rico	840 ± 65^{abc}	-39.2 ± 22.91^{c}	0.74 ± 0.05^{b}	625.2 ± 76.1^{abcd}	18.7 ± 0.2^{ab}
Suwon122	572 ± 32^{de}	-17.22 ± 12.65^{abc}	0.85 ± 0.03^{ab}	488.8 ± 36.4^{bcd}	19.2 ± 0.1^{ab}

interactions within the granule and the amylose structure (Mua & Jackson, 1997; Vamadevan & Bertoft, 2020). For example, Evangeline starch also had about 21% amylose but produced gels with much higher cohesiveness than that of NC-08-036. Furthermore, there were no significant correlations between the amylose percentages and the corresponding SPFF sensory or mechanical texture properties ($r < 0.26$ and $P > 0.34$; Table S4) and no relationship between the instrumental measure of cohesiveness of starch gels with the cohesiveness of SPFF perceived in the mouth (Table 4). Therefore, amylose content alone is not expected to be a good predictor of starch functionality or SPFF texture properties.

3.2 | Influence of sweetpotato starch properties on French fry textures

This study investigated correlations between sweetpotato textures and isolated sweetpotato starch properties, whereas previous publications reported associations between sweetpotato product textures and the overall compositions (Sato et al., 2018; Walter et al., 1997; Yoon et al., 2018). Our study took a deeper look into the potential impact of a component's physiochemical properties on SPFF textural attributes.

3.2.1 | Starch pasting properties in relation to French fry sensory attributes

Sweetpotato starch pasting properties were correlated with several French fry sensory texture attributes (Table 3 and Figures S19–S31). Pasting temperatures were negatively correlated with perceived French fry surface oiliness and inner smoothness, moistness, and fibrousness, whereas peak temperatures were negatively correlated with fry roughness and outer crispness. Perhaps most interestingly, pasting viscosities were positively correlated with perceived fry denseness (Table 3). It is possible that the varying pasting temperatures of starches in fries affected the extent of starch pasting during frying and ultimately the textures (e.g., moistness and smoothness). However, it is important to note that the sweetpotato composition was also highly correlated with these attributes. Like the correlations with pasting temperature, both the dry matter and starch contents were also negatively correlated with SPFF oiliness, inner smoothness, inner moistness, and inner fibrousness (Sato et al., 2018). Further research is warranted to determine whether the characteristics of starch with a lower pasting temperature or the dry matter/starch contents are responsible for the smoothness, moistness, and oiliness of the SPFF.

TABLE 3 Pearson correlation coefficients (r) of sweetpotato starch Rapid Visco Analyzer measured properties to the respective sweetpotato French fry sensory and Texture Analyzer (italicized) measured properties (**P-value <0.01; *P-value <0.05). Data point distributions of significant correlations can be found in the Supporting Information (Figures S19–S31)

Sensory and mechanical	Rapid Visco Analyzer properties						
texture properties	Pasting temp	Peak viscosity	Peak temp.	Trough viscosity	Breakdown	Final viscosity	Setback
Oiliness	−0.53*	−0.23	−0.15	−0.14	−0.29	−0.17	−0.24
Roughness	−0.11	−0.01	−0.58*	−0.06	−0.05	−0.03	−0.07
Overall hardness	−0.36	−0.38	−0.22	−0.41	−0.33	−0.39	−0.32
Fracturability	−0.37	−0.27	−0.23	−0.29	−0.23	−0.27	−0.19
Denseness	−0.01	−0.60*	−0.19	−0.57*	−0.58*	−0.57*	−0.54*
Outer crispness	−0.43	−0.23	−0.50*	−0.28	−0.16	−0.27	−0.25
Inner smoothness	−0.52*	−0.30	−0.32	−0.33	−0.24	−0.31	−0.25
Inner moistness	−0.63**	−0.16	−0.34	−0.23	−0.09	−0.20	−0.11
Inner fibrousness	−0.70**	−0.34	−0.36	−0.23	−0.43	−0.24	−0.25
Cohesiveness	−0.16	−0.17	−0.05	−0.19	−0.16	−0.16	−0.08
Peak force	−0.24	−0.23	−0.01	−0.25	−0.19	−0.22	−0.12
Hardness	−0.30	−0.19	−0.11	−0.23	−0.15	−0.20	−0.11

TABLE 4 Pearson correlation coefficients (*r*) between Texture Analyzer measured properties of sweetpotato starch paste and the respective sweetpotato French fry sensory attributes and Texture Analyzer (italicized) measured properties (*P-value <0.05)

Sensory and mechanical texture properties	Texture analyzer properties			
	Hardness	Adhesiveness	Cohesiveness	Gumminess
Oiliness	−0.34	−0.53*	−0.21	−0.45
Roughness	−0.10	−0.05	−0.32	−0.25
Overall hardness	−0.27	−0.10	−0.45	−0.11
Fracturability	−0.18	−0.04	−0.41	−0.03
Denseness	−0.59*	−0.54*	−0.23	−0.55*
Outer crispness	−0.16	−0.05	−0.46	−0.01
Inner smoothness	−0.21	−0.02	−0.45	−0.05
Inner moistness	−0.01	−0.20	−0.47	−0.19
Inner fibrousness	−0.35	−0.40	−0.07	−0.39
Cohesiveness	−0.15	−0.01	−0.14	−0.10
Peak Force	−0.12	−0.01	−0.29	−0.00
Hardness	−0.08	−0.06	−0.32	−0.05

A unique finding was that starches with higher pasting viscosities were positively correlated with the sensory "denseness" attribute in the respective French fries (Table 3). Therefore, more "dense" sweetpotato fries likely had greater viscosities within the sweetpotato cells that impacted the sensory experience. Denseness was previously identified as an important texture attribute for baked sweetpotato with variation in denseness among genotypes both within and between sweetpotatoes of varying flesh colors (Leksrisompong et al., 2012). Similarly, perceived denseness of the fry interior was one of the key differentiating sensory texture attributes among SPFF prepared from 16 sweetpotato genotypes and a fundamental difference between SPFF and the commonly consumed white potato fries. However, this texture attribute was not correlated with any of the commonly measured chemical components of sweetpotato or sweetpotato fries (Sato et al., 2018). Thus, the association between fry denseness and starch pasting viscosities suggests that sweetpotato starch pasting properties affect the sensorial SPFF denseness. These differences in starch pasting properties are likely due to varying amylopectin molecular structures, where higher ratios of short amylopectin branch chains (DP 6–12) were positively associated with higher peak pasting viscosities (Tong et al., 2020; Zhu et al., 2011). In cooked sweetpotato tissue, the gelatinized starch granules swell and merge into a single "sponge-like" mass (Valetudie et al., 1999). Thus, it is postulated that sweetpotato starches with greater amounts of short amylopectin branches likely induce higher local viscosities within the sweetpotato cell, which may impart a more "dense" mouthfeel.

3.2.2 | Starch gel textural properties in relation to French fry sensory attributes

The starch gel textural properties were also correlated with French fry denseness and oiliness (Table 4). Sweetpotatoes with starches that formed more adhesive but less hard and gummy gels tended to produce sensorially dense fries; and the sweetpotatoes with more adhesive starch gels were correlated with the perception of oilier fries (Table 4). Because the starch in the SPFFs likely did not gel within the 3-min timeframe from the fryer to the sensory analysis test, the correlations between the starch gel textures and SPFF textures are likely due to starch structures that affect both the gelling properties and SPFF textures. For example, starch gel hardness, adhesiveness, and gumminess were correlated to starch pasting viscosity, and starch pasting viscosity was correlated to SPFF denseness.

3.2.3 | No relationship between starch pasting and gel textural properties with French fry instrumental texture analyses

The instrumentally measured textural properties of sweetpotato fries (peak force and hardness) were not significantly correlated to the isolated starch pasting or gel textural properties (Tables 3 and 4). This lack of correlation suggests that differences in the physiochemical properties of the pasted starch, that is contained within the cells, did not directly affect the force needed to break the fry. In potato (*Solanum tuberosum*) French fries, the measured

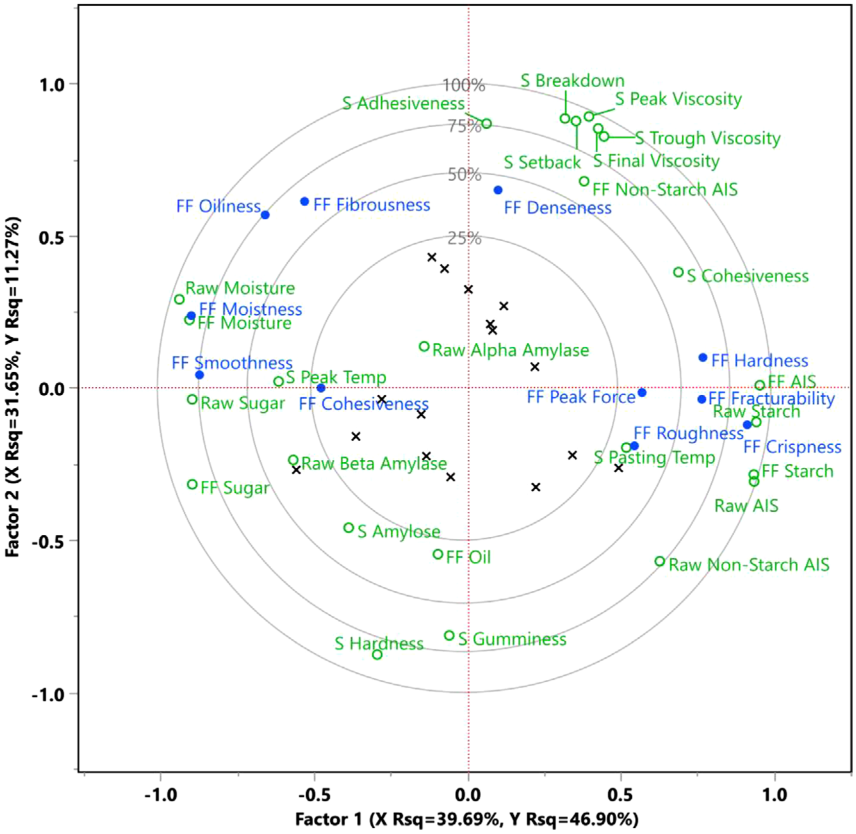

FIGURE 5 Correlation loading plot of a two-factor PLS model with isolated sweetpotato starch property, raw sweetpotato content, and sweetpotato French fry content effects (○, green) to sweetpotato French fry textural attribute responses (●, blue). Black × markers represent the sweetpotato genotypes in the model. Raw sweetpotato and sweetpotato French fry compositions were derived from Sato et al. (2018)

hardness is dictated by the breaking point of the middle lamella between the cells or the rupturing through cells (Singh et al., 2016) but is also associated with the starch content, granule size, starch swelling power, cell size, and cell wall integrity after cooking (Bordoloi et al., 2012). The measured hardness and peak forces of SPFFs were previously correlated with the starch and dry matter contents; however, the hardness of SPFFs made from NC13-487 was two to three times higher than sweetpotatoes with similar starch contents (Sato et al., 2018). Therefore, the starch contents likely affect fry hardness, whereas starch thickening power localized within the cell does not, and other nonstarch SPFF constituents can also affect SPFF hardness. It is postulated that the intercellular polysaccharides (e.g., pectin) and cell wall integrities also contribute to the breaking strength of SPFFs.

3.2.4 | Multivariate modeling of SPFF texture with sweetpotato composition and isolated starch properties

The effects of sweetpotato starch properties on SPFF sensory textures were also investigated using PLS analysis to simultaneously account for all measured starch properties and raw sweetpotato and SPFF compositions (effects) on the SPFF textures (responses). In a two-factor PLS model, 60.1% of the SPFF texture variances were explained and many of the effects and responses were primarily explained by just one of the latent factors. In the correlation loading plot (Figure 5), effects and responses that were positively associated are in proximity to each other, whereas negative associations are in diagonal quadrants (e.g., top right vs. bottom left). Most of the SPFF textures, except fibrousness, oiliness, and denseness, mainly explained latent factor 1 and little of factor 2 (Figures 5 and S32). Similarly, most of the raw sweetpotato and SPFF contents and the starch pasting and peak temperatures also explained latent factor 1 but not factor 2; thus, both sweetpotato composition and starch pasting and peak temperatures were associated with most of the SPFF textures (Figures 5 and S32). This is in agreement with the starch pasting and peak temperatures being correlated to the greatest number of SPFF textures (six of the eight significantly correlated SPFF textures in Tables 3 and 4) and the correlations between moisture and starch contents of SPFF textures reported by Sato et al. (2018). The primary response explaining latent factor 2 was SPFF denseness, whereas the variables were starch pasting viscosities, starch gel adhesiveness, gumminess, and hardness, SPFF nonstarch alcohol-insoluble solids (AIS), and oil contents (Figures 5 and S32). This suggests the SPFF denseness was associated with these starch properties, which agrees with the linear correlations in this study (Tables 3 and 4).

TABLE 5 Variable importance in the projection (VIP) scores and model coefficient signs of variables predicting sweetpotato French fry textures using single factor PLS analyses. Values greater than 1.0 are emboldened and are considered to be important predictors of the PLS models

	Oiliness		Roughness		Hardness		Denseness		Crispness		Smoothness		Moistness		Fibrousness		Cohesiveness	
Variable	**VIP**	+/–	**VIP**	+/–	**VIP**	+/–	**VIP**	+/–	**VIP**	+/–	**VIP**	+/–	**VIP**	+/–	**VIP**	+/–	**VIP**	+/–
S Amylose	0.24		0.28		0.49		0.48		0.50		0.55		0.48		0.58		0.18	
S Peak temp.	0.71		**1.59**	–	0.43		0.49		0.86		0.75		0.73		0.78		0.16	
S Pasting temp.	**1.10**	–	0.31		0.72		0.02		0.74		0.96		**1.14**	–	**1.67**	–	0.51	
S Peak viscosity	0.55		0.03		0.77		**1.55**	+	0.56		0.65		0.46		0.79		0.56	
S Trough viscosity	0.38		0.17		0.82		**1.46**	+	0.61		0.70		0.51		0.52		0.61	
S Breakdown	0.66		0.14		0.67		**1.50**	+	0.48		0.55		0.40		**1.01**	+	0.51	
S Final viscosity	0.43		0.08		0.78		**1.46**	+	0.59		0.68		0.49		0.53		0.52	
S Setback	0.55		0.18		0.64		**1.38**	+	0.51		0.60		0.43		0.54		0.25	
S Hardness	0.66		0.12		0.62		**1.53**	–	0.41		0.50		0.38		0.66		0.65	
S Adhesiveness	**1.12**	+	0.06		0.24		**1.42**	+	0.31		0.30		0.54		0.86		0.05	
S Cohesiveness	0.54		0.97		0.96		0.63		0.90		0.94		0.91		0.42		0.56	
S Gumminess	0.86		0.53		0.30		**1.42**	–	0.13		0.19		0.40		0.80		0.47	
Raw moisture	**1.58**	+	**1.56**	–	**1.33**	–	0.28		**1.53**	–	**1.47**	+	**1.58**	+	**1.57**	+	**1.26**	+
Raw AIS	**1.60**	–	**1.52**	+	**1.36**	+	0.30		**1.52**	+	**1.49**	–	**1.60**	–	**1.55**	–	**1.36**	–
Raw nonstarch AIS	**1.71**	–	**1.07**	+	0.99		0.87		**1.14**	+	**1.23**	–	**1.28**	–	**1.41**	–	**1.61**	–
Raw starch	**1.30**	–	**1.51**	+	**1.33**	+	0.06		**1.47**	+	**1.40**	–	**1.51**	–	**1.37**	–	0.99	
Raw sugar	**1.06**	+	**1.22**	–	**1.49**	–	0.55		**1.28**	–	**1.37**	+	**1.34**	+	0.89		**1.65**	–
Raw alpha amylase	0.56		0.35		0.42		0.27		0.23		0.55		0.52		0.53		0.88	
Raw beta amylase	0.78		0.42		0.66		0.12		0.73		0.75		0.83		0.63		0.30	
FF moisture	**1.42**	+	**1.86**	–	**1.54**	–	0.04		**1.67**	–	**1.46**	+	**1.44**	+	**1.21**	+	**1.65**	+
FF Oil	0.31		0.59		0.23		**1.18**	–	0.52		0.33		0.12		0.45		0.38	
FF AIS	**1.25**	–	**1.71**	+	**1.64**	+	0.44		**1.65**	+	**1.52**	–	**1.47**	–	**1.02**	–	**1.67**	+
FF nonstarch AIS	0.51		0.95		**1.18**	+	**1.83**	+	0.72		0.62		0.42		**1.15**	+	**1.22**	–
FF starch	**1.59**	–	**1.57**	+	**1.38**	+	0.29		**1.59**	+	**1.50**	–	**1.58**	–	**1.46**	–	**1.40**	–
FF sugar	0.98		0.97		**1.50**	–	0.80		**1.30**	–	**1.48**	–	**1.35**	+	0.64		**1.67**	+

The combined effects of sweetpotato starch properties, raw sweetpotato composition, and SPFF composition on SPFF textures were further investigated by performing individual PLS analyses with each SPFF texture (Table 5). Variables that were considered important predictors of individual SPFF textures in the PLS models had VIP scores greater than 1.0, and the model coefficient sign indicated the type of association, positive or negative (Cox & Gaudard, 2013). When accounting for the isolated starch properties, most of the SPFF textures, excluding SPFF denseness, were still primarily associated with raw sweetpotato and SPFF composition as reported in Sato et al. (2018). A new composition that was included in the models in this study was nonstarch AIS content, which was calculated as total AIS minus the starch content. The AIS fraction is composed of cell polymers such as starch, cellulose, hemicellulose, pectin, proteins, lignin, and DNA (Fry, 2010; Noda et al., 1994; Selvendran, 1975). Therefore, the nonstarch AIS content is an estimation of alcohol-insoluble cell wall materials and proteins. Interestingly, SPFF nonstarch AIS content had the highest VIP score in predicting SPFF denseness, whereas other raw sweetpotato and SPFF compositions were not associated with SPFF denseness. When accounting for raw sweetpotato and SPFF compositions, the isolated starch properties were not strong predictors of SPFF textures, except for SPFF denseness (Table 5). Starch pasting temperature was associated with SPFF oiliness, moistness, and fibrousness but sweetpotato compositions had higher VIP values and would likely be better predictors. Also, both the raw sweetpotato and SPFF compositions were essentially equivalent at predicting SPFF textures and had the same positive or negative model coefficient signs (i.e., directionality of associations). However, the associations of nonstarch AIS contents in raw sweetpotato and SPFF with SPFF textures were vastly different. For example, raw nonstarch AIS was associated with SPFF oiliness, roughness, crispness, and smoothness and not hardness or denseness, whereas nonstarch AIS contents of SPFF were not associated with these attributes but highly associated with hardness and denseness. Thus, the changes in the nonstarch AIS fraction must have varied among the genotypes during cooking. The biggest change was likely the cleavage of pectins during heating from β-elimination of the glycosidic linkage of nonmethylated galacturonsyl units (Keijbets & Pilnik, 1974; Plat et al., 1988). Therefore, most of the SPFF textures could be reasonably predicted by the raw sweetpotato composition, but the SPFF denseness, a distinguishing SPFF texture, is likely a function of the cell wall polymers (e.g., pectins and structural proteins) and the local viscosity within the cell from pasted starch. More research is needed to understand the impact of cell wall polymers on SPFF fry textural nuances.

4 | CONCLUSIONS

Isolated sweetpotato starches exhibited varying pasting and gel textural properties among the genotypes. These thermal and viscoelastic differences between sweetpotato starches were hypothesized to result from varying starch structures and granule morphologies. Sweetpotato starch pasting properties and gel viscoelastic properties were correlated with perceived SPFF sensory texture attributes but not with the force required to break the fries. Starch pasting temperatures were negatively correlated with several SPFF textural properties (e.g., smoothness and moistness), thus the cooking characteristics of the sweetpotato starch likely influenced the textural properties of the SPFFs. Notably, the perceived denseness of SPFFs, an important texture attribute of SPFF that was unrelated to sweetpotato proximate composition, was correlated with the starch pasting viscosities and textural properties of starch gels. The range of amylose content among sweetpotato starches was relatively narrow and was not correlated with any SPFF textures. Accounting for raw sweetpotato and SPFF compositions and the isolated starch properties, most SPFF texture attributes were associated with starch pasting temperatures and content. SPFF denseness was positively associated with starch pasting viscosities, starch gel adhesiveness, and the SPFF nonstarch AIS contents. SPFF denseness, a distinguishing SPFF texture, was likely a response of the starch thickening power within the cell and cell wall material strength during frying. Correlations between sweetpotato starch properties and SPFF textures demonstrated that SPFF textures are not solely dictated by starch content but also influenced by the starch's viscoelastic and thermal properties.

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AUTHOR CONTRIBUTIONS

Nicholas Marinos assisted in study design, collected the starch characterization data, interpreted the results, and drafted the manuscript. Matthew Allan conducted statistical analyses of data, interpreted the results, and drafted and revised the manuscript. Suzanne Johanningsmeier interpreted the results and revised the manuscript. Ai Sato assisted in study design and sweetpotato starch extraction and reviewed the manuscript. Van-Den Truong conceived and designed the study and edited the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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REFERENCES

Abegunde, O. K., Mu, T. H., Chen, J. W., & Deng, F. M. (2013). Physicochemical characterization of sweet potato starches popularly used in Chinese starch industry. *Food Hydrocolloids*, *33*(2), 169–177. https://doi.org/10.1016/j.foodhyd.2013.03.005

Albuquerque, T. M. R., Sampaio, K. B., & Souza, E. L. (2019). Sweet potato roots: Unrevealing an old food as a source of health promoting bioactive compounds–A review. *Trends in Food Science & Technology*, *85*, 277–286.

Bordoloi, A., Kaur, L., & Singh, J. (2012). Parenchyma cell microstructure and textural characteristics of raw and cooked potatoes. *Food Chemistry*, *133*(4), 1092–1100. https://doi.org/10.1016/j.foodchem.2011.11.044

Brabet, C., Reynoso, D., Dufour, D., Mestres, C., Arredondo, J., & Scott, G. (1999). *Starch content and properties of 106 sweetpotato clones from the world germplasm collection held at CIP, Peru*. CIP Program Report 1997–98.

Cazzonelli, C. I. (2011). Carotenoids in nature: Insights from plants and beyond. *Functional Plant Biology*, *38*(11), 833–847. https://doi.org/10.1071/FP11192

Cervantes-Flores, J. C., Sosinski, B., Pecota, K. V., Mwanga, R. O. M., Catignani, G. L., Truong, V. D., Watkins, R. H., Ulmer, M. R., & Yencho, G. C. (2011). Identification of quantitative trait loci for dry-matter, starch, and β-carotene content in sweetpotato. *Molecular Breeding*, *28*(2), 201–216. https://doi.org/10.1007/s11032-010-9474-5

Chen, Z., Schols, H. A., & Voragen, A. G. J. (2003). Starch granule size strongly determines starch noodle processing and noodle quality. *Journal of Food Science*, *68*(5), 1584–1589. https://doi.org/10.1111/j.1365-2621.2003.tb12295.x

Collado, L. S., Mabesa, R. C., & Corke, H. (1999). Genetic variation in the physical properties of sweet potato starch. *Journal of Agricultural and Food Chemistry*, *47*(10), 4195–4201. https://doi.org/10.1021/jf990110t

Cox, I., & Gaudard, M. (2013). *Discovering partial least squares with JMP*. SAS Institute Inc.

Cui, R., & Zhu, F. (2019). Physicochemical and functional properties of sweetpotato flour. *Journal of the Science of Food and Agriculture*, *99*(10), 4624–4634. https://doi.org/10.1002/jsfa.9702

Debet, M. R., & Gidley, M. J. (2006). Three classes of starch granule swelling: Influence of surface proteins and lipids. *Carbohydrate Polymers*, *64*(3), 452–465. https://doi.org/10.1016/j.carbpol.2005.12.011

Donado-Pestana, C. M., Salgado, J. M., de Oliveira Rios, A., dos Santos, P. R., & Jablonski, A. (2012). Stability of carotenoids, total phenolics and in vitro antioxidant capacity in the thermal processing of orange-fleshed sweet potato (*Ipomoea batatas* Lam.) cultivars grown in Brazil. *Plant Foods for Human Nutrition*, *67*(3), 262–270. https://doi.org/10.1007/s11130-012-0298-9

Friedman, H. H., Whitney, J. E., & Szczesniak, A. S. (1963). The texturometer—A new instrument for objective texture measurement. *Journal of Food Science*, *28*(4), 390–396. https://doi.org/10.1111/j.1365-2621.1963.tb00216.x

Fry, S. C. (2010). Cell wall polysaccharide composition and covalent crosslinking. In P. Ulvskov (Ed.), *Annual plant reviews*, plant polysaccharides: Biosynthesis and bioengineering (Vol. *41*, pp. 1–42). Wiley-Blackwell. https://doi.org/10.1002/9781444391015.ch1

Gao, M., Huam, J., Moallic, C., Ashu, M. G., Xia, Q., Stewart, L., & Bhatnagar, D. (2014). Structure-related properties of sweetpotato critically impact the textural quality of fried chips. *African Journal of Agricultural Research*, *9*(14), 1113–1123.

Han, X.-Z., & Hamaker, B. R. (2001). Amylopectin fine structure and rice starch paste breakdown. *Journal of Cereal Science*, *34*(3), 279–284. https://doi.org/10.1006/JCRS.2001.0374

Ishiguro, K., Noda, T., Kitahara, K., & Yamakawa, O. (2000). Retrogradation of sweetpotato starch. *Starch - Stärke*, *52*(1), 13–17.

Jane, J., Chen, Y. Y., Lee, L. F., McPherson, A. E., Wong, K. S., Radosavljevic, M., & Kasemsuwan, T. (1999). Effects of amylopectin branch chain length and amylose content on the gelatinization and pasting properties of starch. *Cereal Chemistry*, *76*(5), 629–637. https://doi.org/10.1094/CCHEM.1999.76.5.629

Keijbets, M. J. H., & Pilnik, W. (1974). β-Elimination of pectin in the presence of anions and cations. *Carbohydrate Research*, *33*(2), 359–362. https://doi.org/10.1016/S0008-6215(00)82815-3

Kitahara, K., Nakamura, Y., Otani, M., Hamada, T., Nakayachi, O., & Takahata, Y. (2017). Carbohydrate components in sweetpotato storage roots: Their diversities and genetic improvement. *Breeding Science*, *67*(1), 62–72. https://doi.org/10.1270/jsbbs.16135

Lee, B.-H., & Lee, Y.-T. (2017). Physicochemical and structural properties of different colored sweet potato starches. *Starch - Stärke*, *69*(3–4), 1600001. https://doi.org/10.1002/star.201600001

Leksrisompong, P. P., Whitson, M. E., Truong, V. D., & Drake, M. A. (2012). Sensory attributes and consumer acceptance of sweet potato cultivars with varying flesh colors. *Journal of Sensory Studies*, *27*(1), 59–69. https://doi.org/10.1111/j.1745-459X.2011.00367.x

Loebenstein, G. (2009). Origin, distribution and economic importance. In G. Loebenstein & G. Thottappilly (Eds.), *The sweetpotato* (pp. 9–12). Springer. https://doi.org/10.1007/978-1-4020-9475-0_2

Mua, J. P., & Jackson, D. S. (1997). Relationships between functional attributes and molecular structures of amylose and amylopectin fractions from corn starch. *Journal of Agricultural and Food Chemistry*, *45*(10), 3848–3854.

Noda, T., Takahata, Y., Nagata, T., & Shibuya, N. (1994). Chemical composition of cell wall material from sweet potato starch residue. *Starch - Stärke*, *46*(6), 232–236. https://doi.org/10.1002/star.19940460607

Noda, T., Takahata, Y., Sato, T., Kumagai, T., & Yamakawa, O. (1998). Starch properties and cell-wall material contents in sweet potatoes as affected by flesh color, cultivation method and year. *Journal of Applied Glycoscience*, *45*(1), 1–9. https://doi.org/10.11541/jag1994.45.1

Plat, D., Ben-Shalom, N., Levi, A., Reid, D., & Goldschmidt, E. E. (1988). Degradation of pectic substances in carrots by heat treatment. *Journal of Agricultural and Food Chemistry*, *36*(2), 362–365. https://doi.org/10.1021/jf00080a030

Sato, A., Truong, V.-D., Johanningsmeier, S. D., Reynolds, R., Pecota, K. V., & Yencho, G. C. (2018). Chemical constituents of sweetpotato genotypes in relation to textural characteristics of processed French fries. *Journal of Food Science*, *83*(1), 60–73. https://doi.org/10.1111/1750-3841.13978

Selvendran, R. R. (1975). Analysis of cell wall material from plant tissues: Extraction and purification. *Phytochemistry*, *14*(4), 1011–1017.

Singh, J., Kaur, L., & Rao, M. A. (2016). Textural characteristics of raw and cooked potatoes. In J. Singh & L. Kaur (Eds.), *Advances in potato chemistry and technology* (2nd ed., pp. 475–501). Elsevier Inc. https://doi.org/10.1016/B978-0-12-800002-1.00016-9

Tester, R. F., & Morrison, W. R. (1990). Swelling and gelatinization of cereal starches. I. Effects of amylopectin, amylose, and lipids. *Cereal Chemistry*, *67*(6), 551–557.

Tomlins, K., Owori, C., Bechoff, A., Menya, G., & Westby, A. (2012). Relationship among the carotenoid content, dry matter content and sensory attributes of sweet potato. *Food Chemistry*, *131*(1), 14–21. https://doi.org/10.1016/j.foodchem.2011.07.072

Tong, C., Ru, W., Wu, L., Wu, W., & Bao, J. (2020). Fine structure and relationships with functional properties of pigmented sweet potato starches. *Food Chemistry*, *311*, 126011. https://doi.org/10.1016/j.foodchem.2019.126011

Truong, V. D., Avula, R. Y., Pecota, K. V., & Yencho, G. C. (2018). Sweetpotato production, processing, and nutritional quality. In M. Siddiq & M. A. Uebersax (Eds.), *Handbook of vegetables and vegetable processing* (2nd ed., Vol. *2*, pp. 811–838). John Wiley & Sons Ltd.

Tsakama, M., Mwangwela, A. M., Manani, T. A., & Mahungu, N. M. (2010). Physicochemical and pasting properties of starch extracted from eleven sweetpotato varieties. *African Journal of Food Science and Technology*, *1*(4), 90–98.

USDA-ERS. (2020). Sweet potatoes: U.S. exports by value. USDA Economic Research Service. https://www.ers.usda.gov/data-products/vegetables-and-pulses-data/by-category/

USDA-NASS. (2020). Quick stats. USDA National Agricultural Statistics Service. https://quickstats.nass.usda.gov/

Valetudie, J. C., Gallant, D. J., Bouchet, B., Colonna, P., & Champ, M. (1999). Influence of cooking procedures on structure and biochemical changes in sweet potato. *Starch/Staerke*, *51*(11–12), 389–397. https://doi.org/10.1002/(sici)1521-379x(199912)51:11/12⟨389::aid-star389⟩3.0.co;2-h

Vamadevan, V., & Bertoft, E. (2018). Impact of different structural types of amylopectin on retrogradation. *Food Hydrocolloids*, *80*, 88–96. https://doi.org/10.1016/J.FOODHYD.2018.01.029

Vamadevan, V., & Bertoft, E. (2020). Observations on the impact of amylopectin and amylose structure on the swelling of starch granules. *Food Hydrocolloids*, *103*, 105663. https://doi.org/10.1016/j.foodhyd.2020.105663

Walter, W. M., Collins, W. W., Truong, V. D., & Fine, T. I. (1997). Physical, compositional, and sensory properties of French fry-type products from five sweetpotato selections. *Journal of Agricultural and Food Chemistry*, *45*(2), 383–388. https://doi.org/10.1021/jf960061+

Walter, W. M., Truong, V. D., Wiesenborn, D. P., & Carvajal, P. (2000). Rheological and physicochemical properties of starches from moist- and dry-type sweetpotatoes. *Journal of Agricultural and Food Chemistry*, *48*, 2937–2942.

Wang, S., Nie, S., & Zhu, F. (2016). Chemical constituents and health effects of sweet potato. *Food Research International*, *89*, 90–116.

Waramboi, J. G., Dennien, S., Gidley, M. J., & Sopade, P. A. (2011). Characterisation of sweetpotato from Papua New Guinea and Australia: Physicochemical, pasting and gelatinisation properties. *Food Chemistry*, *126*(4), 1759–1770. https://doi.org/10.1016/j.foodchem.2010.12.077

Yoon, H., No, J., Kim, W., & Shin, M. (2018). Textural character of sweet potato root of Korean cultivars in relation to chemical constituents and their properties. *Food Science and Biotechnology*, *27*(6), 1627–1637. https://doi.org/10.1007/s10068-018-0429-7

Zhu, F., Corke, H., & Bertoft, E. (2011). Amylopectin internal molecular structure in relation to physical properties of sweetpotato starch. *Carbohydrate Polymers*, *84*(3), 907–918. https://doi.org/10.1016/j.carbpol.2010.12.039

Zhu, F., & Wang, S. (2014). Physicochemical properties, molecular structure, and uses of sweetpotato starch. *Trends in Food Science and Technology*, *36*(2), 68–78. https://doi.org/10.1016/j.tifs.2014.01.008

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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