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Processing Treatments for Mitigating Acrylamide Formation in Sweetpotato French Fries

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ABSTRACT: Acrylamide formation in sweetpotato French fries (SPFF) is likely a potential health concern as there is an increasing demand for good-quality fries from carotene-rich sweetpotatoes (SP). This is the first report on acrylamide formation in SPFF as affected by processing methods. Acrylamide levels in SPFF from untreated SP strips fried at 165 °C for 2, 3, and 5 min were 124.9, 255.5, and 452.0 ng/g fresh weight, which were reduced by about 7 times to 16.3, 36.9, and 58.3 ng/g, respectively, when the strips were subjected to processing that included water blanching and soaking in 0.5% sodium acid pyrophosphate before frying. An additional step of strip soaking in 0.4% calcium chloride solution before par-frying increased the calcium content from 0.2 to 0.8 mg/g and decreased the acrylamide levels to 6.3, 17.6, and 35.4 ng/g, respectively. SPFF with acrylamide level of <100 ng/g or several times lower than that of white potato French fries can be obtained by integrating processing treatments commonly used in the food industry.

KEYWORDS: *sweet potatoes, Ipomoea batatas, sugars, asparagine, acrylamide French fries*

INTRODUCTION

Consumer demands for French fries processed from orange-fleshed sweetpotatoes (SP) as a carotene-rich food have increased in recent years.[1] In response to the increasing market demand, many food companies have thus ventured into commercial production of sweetpotato French fries (SPFF). For commercial success, the product should be of consistent quality regardless of root storage duration. Our previous studies demonstrated that consistent quality SPFF can be produced year round from SP roots stored under appropriate conditions. SPFF have relatively low fat content, 10% fresh weight (fw), and high carotene content, 10 mg/100 g fw.[2] However, aside from quality, acrylamide formation in SPFF can be a potential health concern.

Acrylamide is potentially carcinogenic in humans, and its formation is found to be associated with the Maillard reaction in thermally processed foods. Free amino acids, especially asparagine and reducing sugars, are the most important precursors for the acrylamide formation that occurs during the heat processing of foods.[3] Various studies on acrylamide intake indicated that French fries and potato chips (referred to as potato crisps in the United Kingdom and some other places), bread and bakery products, coffee, and breakfast cereals are the main sources of dietary acrylamide exposure.[4,5] French fries containing less than a proposed value of 100 μg/kg are recommended for reducing the dietary acrylamide intake.[6]

Numerous studies have been conducted to determine factors affecting its formation and to develop possible mitigation strategies to limit acrylamide levels in various foods, especially fried potato products.[7−11] The mitigation strategies include lowering reducing sugars and free asparagine in the raw materials through potato cultivar selection, application of appropriate agronomical practices, control of storage conditions (>8 °C), and tuber reconditioning for reduction of reducing sugars before processing.[12−14] Processing strategies recommended for reducing acrylamide formation in potato French fries include having the appropriate shape and size of potato cuts, that is, surface to volume ratio,[15] blanching temperature and time,[16] and soaking in water containing various additives or processing aids including calcium and sodium acid pyrophosphate (SAPP).[10] The effects of frying time, temperature, and oil type on acrylamide formation in fried potato products have been studied in detail.[8,10] Gökmen and others[17] reported a linear relationship between frying time and acrylamide content in potato French fries and an exponential increase with increased frying temperature between 150 and 190 °C. A frying model was developed for a close estimate of acrylamide content in potato French fries as a function of reducing sugar level, strip thickness, frying time, and temperature.[18]

For SPFF, several studies have been reported on the effects of SP cultivars, postharvest handling, processing treatments, and frying conditions on product quality.[2,19−23] However, limited information is available on acrylamide content in SP fries and other SP processed products. Therefore, research in this area would be beneficial to SP processors in delivering good-quality SPFF with low acrylamide levels to the consumers. We report, hereto, the effect of processing treatment and frying time on acrylamide formation in SPFF. To our knowledge, this is the first study on acrylamide

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formation in SPFF as affected by common practices of French fry processing.

MATERIALS AND METHODS

Chemicals. Food grade chemicals, namely, SAPP and anhydrous calcium chloride ($CaCl_2$), were purchased from Spectrum Chemical MFG Corp. (Gardena, CA, USA) and Tetra Chemicals (Woodlands, TX, USA), respectively. High-pressure liquid chromatography (HPLC) grade methanol (99.9%) was purchased from Sigma-Aldrich (St. Louis, MO, USA). Water used for HPLC analysis was purified with a deionized water system (Pure Water Solutions, Hillsborough, NC, USA). Cellobiose and asparagine standards were obtained from Sigma-Aldrich (St. Louis, MO, USA). Acrylamide (>99%) was purchased from Sigma-Aldrich (Diesenhofen, Germany). Potassium hexacyanoferrate, zinc sulfate, and formic acid (98%) were obtained from Merck (Darmstadt, Germany). Carrez I solution was prepared by dissolving 15 g of potassium hexacyanoferrate in 100 mL of water, and Carrez II solution was prepared by dissolving 30 g of zinc sulfate in 100 mL of water. The Oasis MCX solid phase extraction (SPE) cartridges (30 mg, 1 mL) were obtained from Waters Corp. (Berkshire, UK). All other chemicals were of analytical grade (Fisher Scientific, Suwannee, GA, USA).

Sweetpotato Cultivar and French Fry Processing. Orange-fleshed SP (cv. Covington) was grown at the experimental fields of the Sweetpotato Breeding Program (Clinton, NC, USA), North Carolina State University. The harvested roots were cured at 30 °C and 85−90% relative humidity for 7 days and stored at 13−16 °C and 80−90% relative humidity for 4 months prior to sampling for the experiments.

Sweetpotatoes were washed, peeled, and cut into 0.9 × 0.9 cm strips using a manual French fry cutter (model 29, Vollrath, Bloomfield, IN, USA). Strips were trimmed by hand to a uniform length of 9 cm and divided into three batches, one for each processing treatment. For treatment 1 (Trt 1), strips were not subjected to any soaking or blanching treatments. Strips were cut and fried as commonly practiced for home preparation of French fries. A par-frying step was included in Trt 1 for parallel comparison with the other treatments in this study. For treatment 2 (Trt 2), samples were blanched in tap water at 95 ± 2 °C for 3 min using a steam-jacketed kettle. Immediately after blanching, the strips were drained and soaked in 0.5% SAPP at 62 ± 1 °C for 10 min followed by soaking in tap water at 21 ± 1 °C for 10 min. The strips were then drained, placed on a stainless steel rack, and partially air-dried at 65 ± 5 °C for 10 min to obtain up to 10−15% weight loss using a 1600 W food dehydrator (model D-14, The Sausage Maker Inc., Buffalo, NY, USA). For treatment 3 (Trt 3), the materials were processed as described in Trt 2 with an additional step of soaking the blanched SAPP-treated strips in 0.4% $CaCl_2$ at 62 ± 1 °C for 10 min before air-drying. All strips (120 g) were par-fried at 165 °C for 1 min in 22 L of canola oil in an electric fryer (1ER50 Series, Vuncan-Hart Co., Louisville, KY, USA) and drained on absorbent paper towels. This frying temperature is 10 °C lower than the maximum frying temperature recommended by the European Food Safety Authority for white potato French fries.[24] Due to the high reducing sugar content in SP, frying temperatures above 170 °C as commonly applied in potato French fries[8,11] would produce SPFF with an undesirable brown color. Par-fried strips were cooled to room temperature, covered, and frozen at −20 °C. Final frying was also done in canola oil at 165 °C for 2, 3, and 5 min.

Sample Preparation for Chemical Analyses. Samples were collected at each processing step and stored at −20 °C for analyses of dry matter, asparagine, calcium, and sugar contents. For calcium and acrylamide determination, the collected samples were dried for 24 h in a convection oven at 50 ± 1 °C and pulverized using a Mr. Coffee precision coffee grinder (Sunbeam, Boca Raton, FL, USA). Raw SP strips were freeze-dried for several days using a VirTis Genesis 25XL freeze-dryer (Gadiner, NY, USA), operated at −35 to −40 °C, and pulverized as other samples. The dry matter content of all samples was determined by using the oven method at 100 °C for 24 h.

Quantitation of Sugars. Duplicate specimens (5 g) from each frozen sample were ground in 15 mL of boiling 80% ethanol with a Tekmar tissuemizer (type SDT-1810; Tekmar Co., Cincinnati, OH, USA) and centrifuged at 5000 rpm for 10 min. Each sample was extracted two more times with 15 mL of 80% ethanol, and the combined supernatants were brought to 50 mL and filtered with a 0.25 μm syringe filter. Sugars were analyzed using a Shimadzu HPLC system equipped with a SIL-20AC HT autosampler, DGU-20a_3 degasser, LC 20AD pump, CTO-20A column oven, and CBM-20A controller hooked to an Antec Leyden model Decade II electrochemical detector in the pulsed mode using a gold electrode and LabSoultions/LC Solution Acquisition software (Shimadzu Corp., Kyoto, Japan). Sugar separation (glucose, fructose, sucrose, and maltose) was achieved by a 250 × 4 mm CarboPac-PA1 column attached to a 50 × 4 mm CarboPac guard column (Thermo Scientific, Waltham, MA, USA). The eluent was 0.15 N NaOH at a flow rate of 1 mL/min and temperature of 30 °C. An internal standard of cellobiose was used for peak area quantitation of the separated sugars.[25] All standard curves had a goodness of fit coefficient of at least 0.99 with the intercept being set to zero.

Quantitation of Asparagine. Free asparagine was analyzed by HPLC using the method described by Palazoğlu and Gökmen[26] with minor modifications. Duplicate specimens (5 g) from each frozen sample were ground in 25 mL of cold deionized water using a Tekmar tissuemizer (type SDT-1810) for 2 min. An additional 20 mL of cold water was used to rinse the dispersion probe, and the extraction was continued for 5 min with occasional shaking. The suspension was then centrifuged at 5000 rpm and 10 °C for 10 min, and the extract was adjusted to a final volume of 50 mL with cold water. Asparagine was converted to its 9-fluorenylmethylchloroformate (FMOC) by mixing 0.8 mL of the extract with 0.1 mL of 50 mM borate buffer, pH 10, and 0.1 mL of derivatizing agent (2 mg/mL FMOC-Cl reagent in acetonitrile) for 2 min. Hexane was added to remove the excess FMOC-Cl reagent after derivatization. This step was repeated three times to ensure the removal of the unused fluorescent reagent. Aliquots were taken for injection into a Thermo Finnigan HPLC system equipped with a fluorescent detector FL3000 set at 265/340 nm and ChromQuest data acquisition software (Thermo Electron Corp., San Jose, CA, USA). A Zorbax Eclipse Plus C8 column (150 × 4.6 mm, 5 μm) was used, and the fluorescent compound was eluted at a flow rate of 1 mL/min and 25 °C by mixtures of 50 mM sodium acetate buffer (A) and acetonitrile (B) with the following gradient: from 100 to 75% A from 0 to 10 min, from 75 to 55% A from 10 to 17 min, from 55 to 0% A from 17 to 25 min, then to 100% A in 5 min, and equilibrated for 37 min. Asparagine was calculated on the basis of an external standard with a range from 0.05 to 0.2 mM.

Quantitation of Calcium. Samples of SP strips and SPFF were oven-dried at 100 °C for 24 h and ground into powders. Calcium analysis was conducted at the Analytical Spectroscopy Service Laboratory, North Carolina State University, Raleigh, NC, USA. Duplicate specimens (1 g) from each sample were subjected to acid digestion into liquid and diluted further before analysis for calcium concentration using an inductively coupled plasma atomic emission spectromery (Perkin-Elmer Optima 2000DV, Boston, MA, USA).

Quantitation of Acrylamide Formation. All par-fried and finish-fried SP samples were dried at 50 °C for 24 h and ground into fine powder for acrylamide analysis as previously described.[26,27] Sample (1 g) was extracted with 20 mL of 10 mM formic acid in three stages (10, 5, and 5 mL). The coextracted colloids were precipitated with Carrez I and Carrez II reagents. Fat was separated by means of cold centrifugation (0 °C) at 5000 rpm for 10 min. The extract was cleaned up using a cation-exchanger SPE cartridge to remove positive charged coextractives, which may interfere during the mass spectrometric detection of acrylamide. The clear extract was eluted through a preconditioned Oasis MCX cartridge at a rate of 1 drop/s. After the first seven to eight drops had been discarded, the remaining drops were collected and filtered through a 0.45 μm nylon filter prior to analysis.

The samples were analyzed by using a Waters Acquity UPLC system coupled to a TQ detector operated in ESI(+) mode. Chromatographic separations were performed on an Acquity UPLC HSS T3 column using 10 mM formic acid with 0.5% methanol as

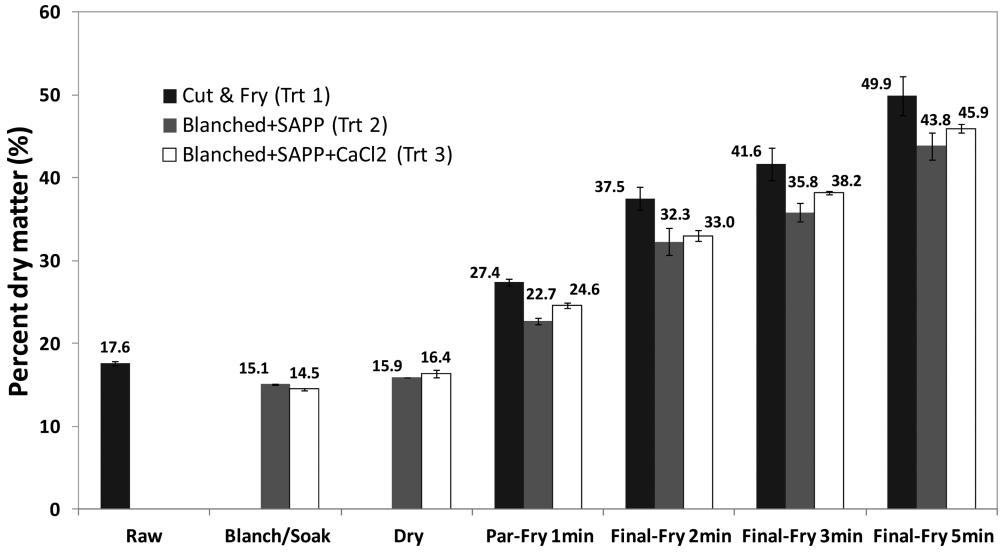

Figure 1. Dry matter content of SP strips at different processing stages.

Figure 2. Typical samples of SP French fry processing: (a) blanched SP strips; (b) par-fried, 165 °C; (c) final frying, 165 °C, 3 min.

mobile phase at the flow rate of 0.3 mL/min. The column was equilibrated at 40 °C, and a Waters Acquity FTN autosampler was held at 10 °C during the analysis. The electrospray source had the following settings: capillary voltage, 0.75 kV; cone voltage, 21 V; extractor voltage, 4 V; source temperature, 120 °C; desolvation temperature, 450 °C; desolvation gas (nitrogen) flow, 900 L/h. Acrylamide was identified by MRM of two channels. Collision gas (argon) had the flow of 0.25 mL/min. The precursor ion $[M + H]^+$ 72 was fragmented, and product ions 55 (collision energy = 9 V) and 44 (collision energy = 12 V) were monitored. The dwell time was 0.2 s for all MRM transitions. Concentration of acrylamide was calculated by means of an external calibration curve built in a range between 1 and 20 ng/mL (1, 2, 5, 10, and 20 ng/mL).

Statistical Analysis. The experiment was conducted with two replicates in a completely randomized design with a covariate. Two samples per replicate were taken for analysis. The General Linear Model procedure in the Statistical Analysis System (SAS, v. 9.2, SAS Institute Inc., Cary, NC, USA) was used to compute the statistical interferences. Group differences were evaluated using t tests with $p < 0.05$ considered to be a statistically significant difference. Means were compared with Duncan's multiple-range test with $\alpha = 0.05$.

RESULTS AND DISCUSSION

Dry Matter, Sugar, and Free Asparagine Contents. The dry matter content of the orange-fleshed SP such as the Covington cultivar used in this study is about 20% after harvest.[28] Respiration and metabolism during storage decreased the dry matter content of raw SP used in this study to 17.6%. Soluble solid leaching out during blanching further decreased the dry matter content to 14.5−15.1% in Trts 2 and 3 (Figure 1). Partial drying of SP strips before par-frying resulted in increases of dry matter content by 5.6−13.6%, which were in accordance with previous studies.[22] The final-fried samples that were fried for 2, 3, and 5 min at 165 °C had dry matter contents of 32.3−49.9% (Figure 1). With the results on dry matter content in Figure 1, all of the fresh weight (fw) data can be converted into dry weight (dw) basis for comparison with information from other studies. For commercial potato French fries, white potato tubers with dry matter content of 20−24% are preferred,[29] and after final-frying, a good-quality product should have residual moisture in the range of 38−45 or 55−62% dry matter.[11,15] After blanching and soaking, potato strips are usually subjected to partial drying to remove surface water, increasing dry matter content, shortening frying time, and consequently reducing acrylamide formation.[17] The SP French fries from all three treatments in this study had lower dry matter contents than commercial potato French fries and a softer creamy texture in the interior. The typical appearances of blanched, par-fried, and final French fry samples of the orange-fleshed SP are shown in Figure 2.

As the name implies, raw SP have a much higher sugar content than white potatoes. The sugar levels of the SP samples from different stages of the three SPFF processing schemes are shown in Figure 3. Raw strips had high concentrations of glucose, 10.22 ± 0.22 mg/g fw (1.0%); fructose, 8.09 ± 0.04 mg/g (0.8%); and sucrose, 41.91 ± 0.63 mg/g (4.2%). The total reducing sugar (sum of glucose and fructose) content was 18.31 mg/g fw (1.8%). This was 9- and 3.6-fold higher than the maximum levels of 0.2 and 0.5% reducing sugar content in white potato cultivars, which was set for limiting the browning color and acrylamide formation in the industrial processing of potato chips and French fries, respectively.[25,29]

Blanching and soaking in water or $CaCl_2$ solution decreased glucose, fructose, and sucrose contents to 0.9, 0.6, and 3.5%,

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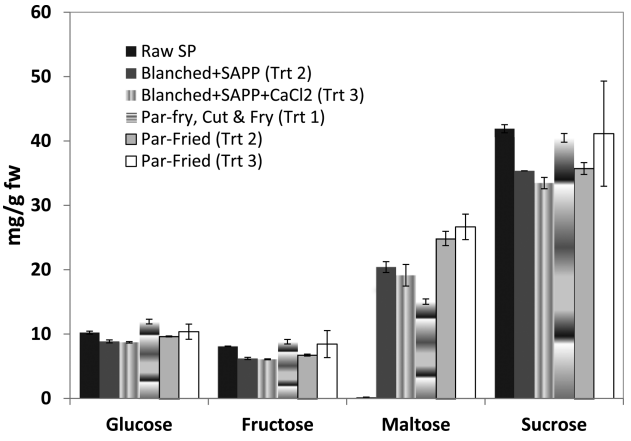

Figure 3. Effects of processing treatments and par-frying on sugar profiles of SP samples.

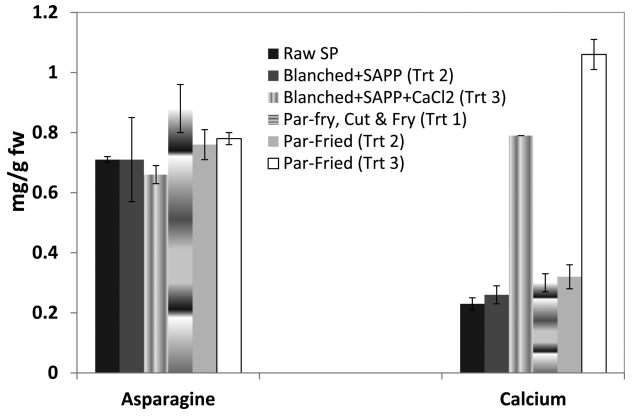

Figure 4. Asparagine and calcium contents in the raw, blanched, and par-fried SP samples.

respectively, accounting for about a 17% reduction of sugar levels in the raw SP strips. This amount of sugar leaching was much lower than the 85% decrease of reducing sugars due to water blanching of potato strips reported by Mestdagh and others.[16] Raw SP strips had negligible maltose content (0.19 ± 0.01 mg/g), which was significantly increased in the blanched and par-fried samples of all three treatments (Figure 3). The starch−maltose conversion during heating is due to hydrolysis of gelatinized starch by endogenous amylases in SP roots.[30,31] The par-fried SP samples of the cut and fry process (Trt 1) had a maltose content of 15.05 ± 0.42 mg/g (Figure 3). This maltose level was lower than the levels of the blanching and soaking treatments, which were 24.86 ± 1.11 mg/g for Trt 2 and 26.66 ± 1.98 mg/g for Trt 3. The differences can be attributed to direct application of the raw SP strips in Trt 1 to the high frying temperature and shorter time (165 °C, 1 min), which were less suitable for amylase hydrolysis of gelatinized starch into maltose as compared to blanching conditions (95 °C, 3 min). The sugar levels, except maltose, were not significantly changed by par-frying ($p > 0.05$). In the final-fried samples, the contents of total reducing sugars (sum of glucose, fructose, maltose) were 50.21−59.93 mg/g (5.02−5.99%) and sucrose levels were 52.34−70.55 mg/g (5.2−7.0%) (Table 1); these compounds provide the natural sweetness and unique flavor of SPFF as compared to white potato French fries.[23]

The asparagine content among the SP samples was found to be from 0.66 to 0.88 mg/g fw (Figure 4), which was at the low end of a range of 0.5−4.2 mg/g fw reported for eight SP varieties harvested in different years in Japan.[32] Lim and others[33] recently reported an asparagine content of 1.97 mg/g dw, equivalent to 0.68 mg/g fw of a purple-fleshed SP cultivar. The concentrations of asparagine in SP are thus much lower than the levels of 1.5−17.7 mg/g fw reported for various white potato cultivars.[13,34,35] Asparagine is the most abundant free amino acid in white potato tubers, accounting for approximately 30% of the total amino acid pool.[13] On a molar basis, asparagine concentration was about 3.7 and 5.6 times higher than that of glucose and fructose, respectively. Therefore, in white potatoes, asparagine has not been considered as a limiting factor in the Maillard reactions and acrylamide formation is mainly governed by reducing sugars during frying of potato products.[11,36] On the contrary, the amount of total reducing sugars in SP was 25 times more than that of asparagine, suggesting that asparagine is likely a limiting factor in acrylamide formation during frying of SP strips. Okuno and others[37] reported a high correlation ($R^2 = 0.803$) between free asparagine content in 15 SP varieties and acrylamide levels of 5 mm thick root slices fried in soybean oil for 4 min at 197 °C. However, there was no significant correlation between acrylamide formation with either glucose or fructose concentration in the fried crisps. In cereals such as wheat, in which the

Table 1. Sugar, Asparagine, and Calcium Content in Sweetpotato Samples As Affected by Final-Frying Time[a]

sample/treatment	frying time at 165 °C (min)	glucose (mg/g fw)	fructose (mg/g fw)	maltose (mg/g fw)	sucrose (mg/g fw)	asparagine (mg/g fw)	calcium (mg/g fw)
1. cut and fry	2	14.16 ± 1.26 ab	13.64 ± 1.58 abc	14.76 ± 1.38 f	64.40 ± 2.13 ab	0.77 ± 0.03 ab	0.35 ± 0.02 cd
(Trt 1)	3	14.71 ± 0.92 ab	11.85 ± 1.73 bcd	25.02 ± 6.89 cde	65.12 ± 5.27 ab	0.69 ± 0.06 bcd	0.39 ± 0.04 cd
	5	14.82 ± 0.68 ab	14.53 ± 1.26 ab	25.84 ± 9.97 bcde	70.55 ± 4.82 a	0.54 ± 0.10 cde	0.42 ± 0.00 cd
2. blanched + SAPP	2	11.39 ± 1.34 c	9.98 ± 1.57 de	29.30 ± 1.96 abcd	52.34 ± 5.36 d	0.67 ± 0.03 bcd	0.40 ± 0.11 c
(Trt 2)	3	13.87 ± 1.47 ab	10.83 ± 1.68 cde	25.51 ± 7.78 cde	62.89 ± 5.63 bc	0.65 ± 0.05 bcd	0.45 ± 0.09 f
	5	14.92 ± 1.97 a	15.37 ± 3.04 a	26.14 ± 9.35 bcde	64.87 ± 3.45 ab	0.53 ± 0.00 cde	0.46 ± 0.13 c
3. blanched +	2	12.73 ± 0.92 b	11.73 ± 0.81 bcd	34.00 ± 4.98 ab	58.42 ± 3.99 cd	0.65 ± 0.04 bcd	1.31 ± 0.07 b
SAPP + $CaCl_2$	3	13.56 ± 0.13 ab	11.23 ± 1.07 cde	35.14 ± 0.25 a	61.02 ± 0.31 bc	0.55 ± 0.06 cde	1.48 ± 0.08 ab
(Trt 3)	5	14.16 ± 0.21 ab	13.36 ± 0.46 abc	30.05 ± 2.34 abc	63.51 ± 0.94 bc	0.42 ± 0.08 e	1.62 ± 0.10 a

[a]Values within columns having the same letter are not significantly different ($p > 0.05$).

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sugar concentrations are relatively higher as compared with free amino acids, the asparagine level can be a limiting factor in acrylamide formation. Selection of wheat cultivars and growing conditions for low asparagine content is among the recommended practices in mitigating acrylamide formation in heated wheat products.[38]

Processing Treatments and Acrylamide Formation. The cut and fry process without par-frying is one of the common methods for home preparations of French fries. In this study, a par-frying step was inserted in Trt 1 for comparison with the processing effects in Trts 2 and 3. The acrylamide concentration in the par-fried SP strips of the cut-fry process was 10.7 ng/g, which linearly increased to 125−452 ng/g on a fresh weight basis (Figure 5) and 324−874 ng/g on a dry

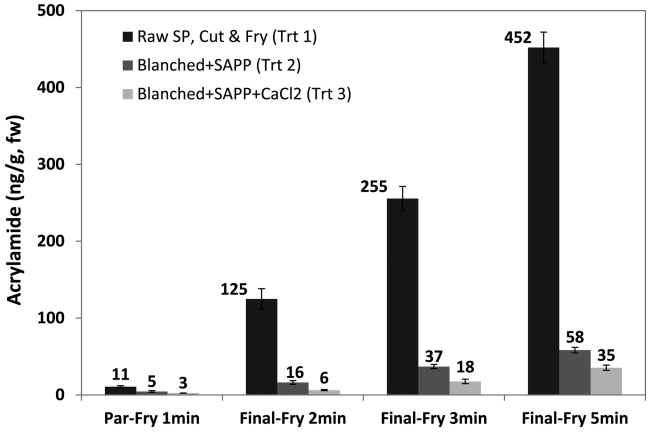

Figure 5. Acrylamide levels in sweetpotato French fries (ng/g fresh weight).

weight basis during final frying at 165 °C for 2, 3, and 5 min. The linear relationship between acrylamide formation and frying time was in accordance with the previous studies on white potato French fries.[18] The acrylamide levels obtained for the nonblanched SPFF samples (Trt 1) (Figure 5) were within the 50−1823 ng/g range of acrylamide content in white potato French fries from various commercial varieties and breeding lines.[34] Acrylamide levels up to 2970 ng/g were reported for home preparation of white potato French fries from potato varieties with wide variations in reducing sugars, 0.015−0.788% fw.[35] Mestdagh and others[16] found an acrylamide level of 833 ng/g from unblanched strips of a potato variety having low reducing sugars (0.061%) fried at 180 °C for 5 min. Commercial white potato French fries in Canada had acrylamide levels that fluctuated from 60 to 1800 ng/g.[34] Acrylamide data gathered from food monitoring in 2007−2010 by the European Food Safety Authority indicated a range of 277−356 μg/kg in white potato French fries.[39,40]

Unlike white potato French fries, information on acrylamide levels in fried SP products is very limited. Acrylamide levels up to 3000 ng/g were formed in 0.5 cm thick root slices of different SP varieties fried at 197 °C for 4 min.[37] The type of vegetable oil and the number of batches fried consecutively in the same oil affect acrylamide formation. The levels of acrylamide varied from 296 to 2019 ng/g in fried chips of a SP cultivar, which were deep-fried in different vegetable oils for 10 consecutive frying sessions, 2 min each at 180 °C.[32] On the basis of the regression of the browning index and the acrylamide content among the fried and roasted food items from different roots and tubers in Africa, the fried SP had the highest estimated acrylamide formation of 1043 ng/g.[41] Sweetpotato fries with acrylamide content of 136.3−366.1 ng/g were among the acrylamide survey of traditional snacks in Thailand.[42]

The results presented in Figure 5 demonstrate the beneficial effect of blanching and soaking SP strips in 0.5% SAPP (pH 4.4) to reduce acrylamide formation in SPFF. Blanching and soaking SP strips in SAPP as described in Trt 2 significantly ($p < 0.05$) reduced the acrylamide content to levels of 16, 37, and 58 ng/g in the final SPFF fried for 2, 3, and 5 min, respectively. The reductions were equivalent to 85−87% on fw (Figure 5) and 83−85% on dw (based on the dry matter content in Figure 1), as compared to the SPFF samples of the cut and fry process (Trt 1). Leaching out of the acrylamide precursors, reducing sugars and asparagines (Figures 3 and 4) contributed to the acrylamide reduction in the SPFF samples. It has been demonstrated that acrylamide formation mainly occurred at the surface of the white potato French fries.[6] Therefore, any processing treatments that result in decreasing the levels of reducing sugars and asparagine on the strip surface would be effective strategies in mitigating acrylamide formation. Further studies need to be conducted to determine the blanching and soaking effects on chemical components at the outer layers of SP strips and acrylamide formation in SPFF. Blanching is commonly practiced in the industrial processing of white potato French fries to inactivate oxidases associated with enzymatic browning and to develop a layer of gelatinized starch, which reduces oil absorption and improves the texture of the fried products. Acrylamide content in potato French fries was reduced from 833 ng/g in the unblanched treatment to 365 ng/g or 56% reduction and to 254 ng/g or 70% reduction by blanching white potato strips in tap water and industrially used blanching water before frying, respectively.[16]

Soaking the potato cuts in acidic solutions, for example, SAPP, citric acids, and other organic acids to reduce darkening has also been reported as a effective way to reduce acrylamide formation in white potato French fries.[10] The SAPP treatment has also been applied in processing of various SP products including purees, chips, and French fries.[23,31] Measurements of pH on the surface of SP strips was performed using a flat electrode of a pH meter (Accumet electrode 13-620-299, Fisher Scientific Accumet AR50). The results showed that the water-blanched SP strips had a pH of 6.2, which was decreased to 5.2 after soaking in 0.5% SAPP for 10 min at 65 °C. Jung and others[43] reported that soaking the potato cuts in citric acid and other organic acid has a mitigating effect by protonating asparagine amino groups at low pH and preventing the formation of Schiff bases, intermediates in the Maillard reaction and acrylamide formation.

Soaking the blanched SAPP-treated strips in 0.4% $CaCl_2$ solution (Trt 3) further decreased the acrylamide levels to 6, 18, and 35 ng/g in the final SPFF fried for 2, 3, and 5 min, respectively (Figure 5). These reductions were equivalent to 40−62% on fresh weight and 42−62% on dry weight as compared to the SPFF samples with no $CaCl_2$ (Trt 2). Therefore, the combined effects of water blanching and soaking SP strips in SAPP and $CaCl_2$ resulted in 92−95% reduction of acrylamide formation in the final frying of SPFF. Soaking the blanched SP strips in 0.4% $CaCl_2$ resulted in a 3.4-fold increase in calcium content (Figure 4). Calcium content in the potato strips after soaking was not always measured in previous studies on acrylamide formation in potato French fries.[9,10] Gökmen and Senyuva[9] reported that dipping potato strips in 0.1 M

$CaCl_2$ solution inhibited the acrylamide formation by up to 95% during frying. In the same mechanism, Kalita and Javanty[44] reported that soaking the potato strips in 0.001, 0.01, and 0.1 M vanadyl sulfate solutions before frying can reduce acrylamide formation by 30.3, 53.3, and 89.3%, respectively. It was postulated that cations such as Na^+, Ca^{2+}, and VO^{+2} could interact with asparagine and prevent the Schiff base reaction involved in acrylamide formation.

In summary, blanching the SP strips and using processing aids and additives, such as SAPP and $CaCl_2$, were effective in reducing acrylamide formation in SP French fries. These processing treatments, especially blanching and SAPP soaking, have been widely used in SP processing and unlikely affected SPFF sensory quality. Overall acceptability scores of SPFF prepared with these treatments were rated >6.0 on a nine-point hedonic scale as reported in previous studies.[2,23] Unlike white potatoes, SP contain low asparagine and high reducing sugar levels, and therefore asparagine is likely a limiting factor in acrylamide formation in SP fried products. Acrylamide formation in SPFF linearly increased with frying time. SPFF with acrylamide levels of <100 ng/g or several times lower than those of regular white potato French fries can be obtained by integrating processing treatments commonly used in the food industry.

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Notes

Mention of a trademark or proprietary product does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture or North Carolina Agricultural Research Service nor does it imply approval to the exclusion of other products that may be suitable.

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