Reduction of Acrylamide Formation in Potato Chips by Low-temperature Vacuum Frying

C. GRANDA, R.G. MOREIRA, AND S.E. TICHY

ABSTRACT: Potatoes and other foods that have a high content of the amino acid asparagine and a high accumulation of reducing sugars are subject to the formation of acrylamide upon frying. The objectives of this research were (1) to analyze the level of acrylamide formed during deep-fat frying of potato chips and (2) to evaluate means of reducing acrylamide in potato chips by using different potato cultivars and vacuum frying. Several potato cultivars were used in this research, including Innovator (I), NDTX 4930-5W (N), ATX 854 04-8W (ATw), Atlantic (A), Shepody (S), ATX847806-2Ru (ATr), and White-Rose (W). An electric bench-top (atmospheric conditions)-type fryer was used to fry the potatoes. Three temperatures were used: 150 °C, 165 °C, and 180 °C. The vacuum frying experiments were performed at 118 °C, 125 °C, and 140 °C and a vacuum pressure of 10 Torr. The potatoes were sliced (1.5-mm thick) and fried for different lengths of times. For potatoes fried at 165 °C (for 4 min) at atmospheric conditions, the acrylamide contents were 5021 ± 55 ppb (W), 552 ± 25 ppb (I), 358 ± 50 ppb (N), 397 ± 25 ppb (ATw), 646 ± 55 ppb (A), 466 ± 15 ppb(S), and 537 ± 14 ppb (ATr). Vacuum frying reduced acrylamide formation by 94%. Results showed that both cultivar and modified frying systems can play an important role in reducing acrylamide formation in fried potatoes. As the frying temperature decreased from 180 °C to 165 °C, acrylamide content in potato chips reduced by 51% during traditional frying and by 63% as the temperature decreased from 140 °C to 125 °C in vacuum frying. Increased frying time increased acrylamide formation during traditional frying for all temperatures and frying methods analyzed. However, the effect on acrylamide concentration was greater for the traditional frying than the vacuum frying.

Keywords: acrylamide, vacuum, frying, potato, temperature

Introduction

In the past 40 years, the use of deep-fat frying processes in the United States and Europe has increased greatly. Many of these products are snack foods with an oil content varying from 6% (roasted nuts) to 40% (potato chips) (Moreira and others 1999). In the United States, about 1.2 billion pounds of potato chips are consumed each year (FSA/USDA 2002). The production of potato chips and shoestring potatoes alone amount to approximately 50 million tons annually (FSA/USDA 2002). However, recent studies (Tareke and others 2000) have shown that *acrylamide*, a genotoxic carcinogen, is formed during high-temperature processes, including frying.

Among several deep-fat frying technologies, vacuum frying has a significant strategic importance for future fried food manufacturing. The technology offers significant benefits such as the improvement of fried product safety and quality and reduced oil oxidation because of the low-temperature processing. The recent studies and interests in vacuum frying applications (Garayo and Moreira 2002) and the development of new fryer designs (Moreira and others 1999) provide the incentive for an in-depth study of acrylamide generation during frying, so a better process can be designed to reduce the formation of this toxic product in fried products.

Researchers in Sweden 1st reported the presence of acrylamide in foods in April 2002. Following that, analysis conducted on samples collected in the United States, United Kingdom, Norway, and Switzerland have verified the Swedish observation that acrylamide is formed primarily in carbohydrate-rich food cooked at high temperature (EC 2002).

Among the different food products analyzed, the highest levels of acrylamide have been found in French fries, potato chips, and other fried, deep-fat fried, or oven-cooked potato products, together with some crisp bread, biscuits, crackers, and breakfast cereals (Tareke and others 2000). Overcooked French fries showed a very high level of acrylamide (>10 ppm), indicating that frying temperature and frying time influence acrylamide formation (WHO 2002). Within each food group evaluated so far, considerable variations in acrylamide levels have been observed, suggesting that heat processing has a marked effect on the levels of acrylamide in the products. Modifying the cooking process could probably reduce the amount of acrylamide in foods.

The chemical mechanism governing acrylamide formation during heat treatment in foods is unclear. The Maillard reaction has been suggested to play an important role in the formation of acrylamide. Mottran and others (2002) found that asparagine, a major amino acid in potatoes and cereals, is the crucial component in the production of acrylamide by the Maillard reaction pathway. They showed that Maillard-driven generation of flavor and color in thermally processed foods can be linked to the formation of acrylamide.

In potato used for the manufacture of potato chips, the dominant amino acid is asparagine (40% to the total amino acid content) (Martin and Ames 2001). These findings indicate that the Maillard reaction involving asparagine can produce acrylamide, thus explaining the increased concentration of acrylamide in certain plant-derived foods after cooking.

Stadler and others (2002) confirmed that early Maillard reaction products (such as N-glycosides) are acrylamide precursors in thermal decomposition reactions. In food-processing systems that use

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Table 1—Characteristic of different potato cultivars used in this study

Cultivar	Characteristic	Utilization
Shepody	Long; smooth to lightly netted buff skin; medium deep eyes, evenly distributed; white flesh.	Excellent for boiling, baking, and french frying, unsuitable for chipping. Good potential for count carton trade and all season processing.
Innovator	Long oblong; large to very large; russetted tan colored skin; shallow eyes, evenly distributed; pale yellow to yellowish white flesh	Fairly firm to floury after cooking texture; suitable for fresh market and processing for chips.
Atlantic	Oval to round, smooth; lightly netted to heavily scaled white skin; shallow white eyes; white flesh.	Good for boiling and baking, excellent for chipping and french frying.
White-rose	Large, long, elliptical, flattened, usually irregular; smooth white skin; numerous medium-deep eyes; white flesh.	Good for boiling and baking; unsuitable for chipping.
ATX847806-2Ru Russet type	Oblong russet, parentage (A7938-1 x COA7906-5), cross made in Idaho and selected in Texas.	Dual purpose. Very good for boiling (mealy texture) and baking (moist texture); excellent for french frying.
NDTX 4930-5W (white-chipping type)	Round white, parentage (ND860-2 x A7961-1), cross made in North Dakota and selected in Texas	Chipping
ATX 854 04-8W	Round white, parentage (Gemchip x ND860-2). Cross made in Idaho and selected in Texas.	Chipping

high temperature and water loss, N-glycoside formation could then be favored.

Although these results have shown that the Maillard reaction is an important route for acrylamide formation, with the data and knowledge available today, it is not possible to exclude any other possibilities. A multitude of reaction mechanisms are probably involved, depending on food composition and processing conditions. More research is needed before any conclusion can be drawn concerning precursors, reaction routes, and conditions for acrylamide formation in terms of reactants, time, temperature, pH, water activity, and so forth.

Jung and others (2003) showed that lowering the pH with citric acid before frying was effective in diminishing acrylamide formation (by about 73%) in French fries when fried for 6 min at 190 °C in an atmospheric fryer. However, according to Pedreschi and others (2004), the effect of citric acid immersion on acrylamide reduction was not obvious in their experiment with potato chips fried at 170 °C and 190 °C. On the other hand, blanching led to a significant reduction in acrylamide content of their chips. Haase and others (2003) reported that by lowering the frying temperature of potato chips from 185 °C to 165 °C, it was possible to reduce the acrylamide formation by half.

The objective of this study was to determine how much acrylamide is formed during deep-fat frying using different potato cultivars. There is a lack of information regarding the relationship between processing conditions and acrylamide formation in deep-fat fried products. In addition, alternative deep-fat frying technologies such as vacuum frying were investigated as a potential method to reduce acrylamide formation in fried foods.

Materials and Methods

Potato samples

Seven potato cultivars were used in this research: Innovator (I), NDTX 4930-5W (N), ATX 854 04-8W (ATw), Atlantic (A), Shepody (S), ATX847806-2Ru (ATr), and White-Rose (W). Table 1 shows the main characteristics of these potatoes. The potatoes were obtained from the Texas A&M Univ. Horticultural Dept. (fresh harvested potatoes from the 2003 season) and stored in a cooling chamber at a temperature range of 10 °C to 12 °C and a relative humidity of 55%. The potatoes were taken out of storage at least 12 h before frying to allow for room temperature equilibration and for the reducing sugar contents to decrease. Once the potatoes were washed, peeled, and sliced (1.5 ± 0.1 mm), they were rinsed for 2 min and blotted in paper towels to remove surface water before frying. A 4.5-cm dia cutter mold was used to cut the slices into identical shapes.

Vacuum frying experiments

A detailed description of the process is described elsewhere (Garayo and Moreira 2002). Figure 1 illustrates a schematic of the vacuum system. The temperatures used were 118 °C, 125 °C, and 140 °C and a vacuum pressure of 10 Torr. The vacuum vessel was set to the target temperature and allowed to operate for 1 h before frying started. Fresh vegetable oil was used in all experiments. About 5 to 6 slices of potatoes (20 to 25 g) were fried each time.

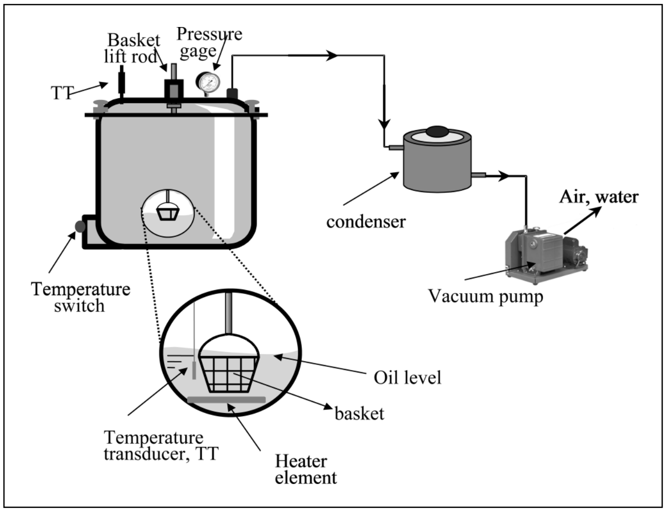

Figure 1—Schematic of the vacuum frying apparatus

Table 2—Experimental design

Potato variety	Frying method	Temperature (°C)	Frying time (s)	PQA[a]
Shepody	Traditional	165	240	AC, C, Tx, MC
	Vacuum	118	480	AC, C, Tx, MC
Innovator	Traditional	165	240	AC, C, Tx, MC
	Vacuum	118	480	AC, C, Tx, MC
Atlantic	Traditional	150,165, 180	60, 120, 180, 240, 300, 360	AC, C, Tx, MC
	Vacuum	118, 125, 140	60, 120, 240, 360, 480, 600	AC, C, Tx, MC
White-rose	Traditional	165	240	AC, C, Tx, MC
	Vacuum	118	480	AC, C, Tx, MC
ATX847806-2Ru	Traditional	165	240	AC, Tx, MC
	Vacuum	118	480	AC, Tx, MC
NDTX 4930-5W	Traditional	165	240	AC, C, Tx, MC
	Vacuum	118	480	AC, C, Tx, MC
ATX 854 04-8W	Traditional	165	240	AC, C, Tx, MC
	Vacuum	118	480	AC, C, Tx, MC

[a]PQA = product quality attributes, AC = acrylamide content, C = color, Tx = texture, MC = moisture content.

Once the potato slices were fried, they were allowed to cool to room temperature, dried with paper towels, and stored in polyethylene bags for further analysis.

Atmospheric frying experiments

An electric fryer (Hobart model HK3-2, Hobart Corp, Troy, Ohio, U.S.A.) was used. This is a bench-top type fryer with a frying oil capacity of 7.5 L. About 50 to 60 g of potato slices were fried in each batch. Three frying temperatures were used (150 °C, 165 °C, and 180 °C).

Acrylamide measurement

The method used (Liquid Chromatography/Mass Spectrometry/Mass Spectrometry) for acrylamide detection in this study is based on the protocol developed by Dr. Steven Musser and colleagues from the U.S. Food and Drug Administration with slight modification (FDA 2002). The samples were homogenized, and 9.96 mL of H_2O and 40 μL of the internal standard (5 ng/mL $^{13}C_3$ acrylamide in 0.1% formic acid) was added to 1 g of the homogenized sample. The samples were mixed for 20 min with a rotating shaker. Samples were then centrifuged at 9000 rpm for 30 min in 50-mL centrifuge tubes, and 5 mL of the supernatant was further centrifuged (at 5000 rpm for 30 min) in a Maxi-Spin filter tube (Maxi-spin filter tube, 0.45-μm PVDF-Alltech, Alltech Assoc., Deerfield, Ill., U.S.A.). A solid-phase extraction (SPE) cartridge (OASIS HLB 6 cc solid-phase extraction, Waters Corp., Milford, Mass., U.S.A.), activated with methanol (3.5 mL) and washed with water (3.5 mL), was used to trap nonpolar interferences by adsorption in the recombined supernatant (1.5 mL). The acrylamide-containing fraction from SPE cartridge was eluted with 0.5 mL of water. Then, it was further eluted with 1.5 mL of water, and this eluted fraction was collected. A mark was placed on outside of Varian SPE cartridge (Bond Elut - Accucat, mixed mode, C8, SAX and SCX; 3-mL solid-phase extraction cartridge, Varian Inc., Harbor City, Calif., U.S.A.) at a height of 1 mL above the sorbent bed. The Varian SPE cartridge was conditioned with 2.5 mL methanol, followed by 2.5 mL of water. The fraction collected from the SPE cartridge (1.5 mL) was loaded in the Varian SPE and eluted to the 1-mL mark before collecting the remainder of the eluted portion. The sample was filtrated with a 0.22-μm filter (Fisherbrand, Fisher Scientific Intl., Pittsburg, Penn., U.S.A.) and analyzed by LC/MS/MS at room temperature using a Waters C-48 column.

Specific gravity measurements

Specific gravity (SG) was determined following the underwater weight method, as described in the Chipping Potato Handbook (SFA 1995).

pH and reducing sugars

Three to four potato slices were crushed and juice was squeezed from them, following the procedure by Jung and others (2003). The pH of the juice was then measured with a pH meter (Cole-Parmer Instrument Co., Vernon Hills, Ill., U.S.A.). The same juice was analyzed for reducing sugar content with Glucose Test Paper Strips (Precision Labs, Inc., West Chester, Ohio, U.S.A.), using the directions provided by the manufacturer. The strip was submerged in the solution for 1 to 2 s. Then, the strip was removed, and after 60 s the color of the strip was compared with a color chart for 0%, 0.1%, 0.25%, 0.5%, and 2% sugar content. Intermediate values were interpolated. Tests were done in triplicate.

Moisture content of raw potatoes

Potato tubers have considerable variability in initial moisture content from potato to potato. To account for this variability, the initial moisture content of each potato was measured before the potato slices were fried. The initial moisture content was determined by drying samples of 5 g of the potato (slices) to a constant mass for 72 h at 105 °C (AACC 1986). The tests were done in triplicate. Values were calculated on a wet-weight basis.

Moisture content of potato chips

Potato chips were ground in a coffee grinder after frying. Moisture content was determined by weight loss after drying 5-g samples of ground chips in a forced air oven at 105 °C for 24 h (AACC 1986). The tests were performed in duplicate. Values were calculated on a wet basis.

Texture

A rupture test was performed on the fried potato chips (Garayo and Moreira 2002) obtained at different frying times using a TA-XT2 Texture Analyzer (Texture Technologies Corp., Scardale, N.Y., U.S.A.). Tests were done in 10 replicates.

Color

The color of the potato chips was measured using a Hunter Lab

Table 3—Acrylamide content of different potato cultivars fried using 2 different frying methods[a]

	Frying methods				Traditional[b]		Vacuum[c]	
Cultivar	SG[d]	Sugar (%)	pH	MC_i[e] (%wb)	Acrylamide (ppb)	MC_f[f] (%wb)	Acrylamide (ppb)	MC_f (%wb)
Innovator	1.07 ± 0.01	0.25 ± 0.10	6.05 ± 0.06	84.9 ± 0.7	552 ± 25	0.97 ± 0.08	35 ± 2	1.81 ± 0.21
NDTX4930-5W	1.06 ± 0.01	0.08 ± 0.01	6.13 ± 0.07	84.2 ± 0.1	358 ± 50	1.56 ± 0.02	ND[g]	2.25 ± 0.23
ATX85404-8W	1.07 ± 0.01	0.03 ± 0.01	6.22 ± 0.06	82.1 ± 0.4	397 ± 25	1.30 ± 0.2	25 ± 3	1.79 ± 0.06
Atlantic	1.08 ± 0.01	0.20 ± 0.10	6.10 ± 0.07	77.6 ± 1.2	466 ± 15	1.13 ± 0.05	75 ± 9	1.68 ± 0.05
Shepody	1.07 ± 0.01	0.18 ± 0.10	6.04 ± 0.07	82.8 ± 0.9	537 ± 14	1.57 ± 0.01	38 ± 2	1.54 ± 0.01
ATX847806-2Ru	1.06 ± 0.01	0.13 ± 0.05	6.19 ± 0.07	83.1 ± 0.0	1554 ± 50	1.05 ± 0.01	44 ± 9	1.56 ± 0.01
White-Rose	1.07 ± 0.01	0.34 ± 0.10	6.14 ± 0.06	85.1 ± 0.2	5021 ± 45	1.53 ± 0.02	437 ± 12	1.38 ± 0.2

[a]Values are means of 4 replicates. Values after ± indicate standard deviation.
[b]4 min at 165 °C (atmospheric conditions).
[c]8 min at 118 °C (10 torr, vacuum conditions).
[d]SG = specific gravity.
[e]MC_i = raw potato moisture content.
[f]MC_f = final moisture content
[g]ND = not detectable.

Colorimeter Labscan XE (Hunter Associates Laboratory, Reston, Va., U.S.A.). Measurements were taken for 10 chips of each frying condition and potato variety, and 2 readings were taken for each potato chip by rotating the chip 180°. Ten replicates were done.

Experimental design

The experimental setup is shown in Table 2. The effect of potato variety, oil temperature, and frying methods on the acrylamide content, color, and texture of the chips was evaluated using a factorial design with 7 levels for potato variety, 3 levels for temperature, and 2 levels for frying methods. The Atlantic variety was selected to evaluate the effect of oil temperature and frying methods on the acrylamide content. This variety was selected because it is very good for chipping and was the most abundant at our lab. The frying temperature-time conditions (240 s at 165 °C and 480 s at 118 °C) allowed the Atlantic chips to reach final moisture contents of about 1.3% (wb). The traditional frying conditions produced chips with good quality attributes in terms of oil content, texture, and color (Garayo and Moreira 2002).

Statistical analysis

Analysis of variance, Duncan's New Multiple range test ($\alpha = 0.05$) and Tukey's tests were used to determine differences among treatments. The statistical analysis of the data was conducted using PlotIt (version 3.2, 1999; Scientific Programming Enterprises, Haslett, Mich., U.S.A.) software package. Statistical significance was expressed at the $P < 0.05$ level. The experiments were performed at least in duplicate.

Results and Discussion

Acylamide in chips prepared from different potato variety

Table 3 shows the relationship of acrylamide content for the 7 potato cultivars of potato chips processed under atmospheric frying (traditional) and vacuum frying. For the potatoes fried by the traditional method (at 165 °C for 4 min), the cultivar that showed the greatest acrylamide content was the White-rose variety (5021 ppb), followed by ATX847806-2Ru (1554 ppb). The Shepody, Atlantic, and Innovator cultivars showed acrylamide contents ranging from 470 to 552 ppb. The lowest acrylamide contents were obtained with chips from the NDTX 4930-5W and ATX 854 04-8W cultivars, with 358 and 397 ppb, respectively.

For the potato chips fried using vacuum frying (at 118 °C, 10 Torr, 8 min), the acrylamide content was always lower compared with those chips fried with the traditional fryer (ranging from 85% to 99% reduction). The White-rose cultivar had the greatest (437 ppb) and ATX 854 04-8W cultivar the lowest (25 ppb) acrylamide content. The other varieties produced potato chips with acrylamide content varying from 35 ppb (Innovator) to 75 ppb (Atlantic).

The main characteristics of the varieties in terms of SG, pH, and sugar content are also shown in Table 3. There were no significant differences in pH and SG values among the cultivars analyzed in this study. However, the average reducing sugar content of White-rose potato was significantly greater (0.34%) than the other varieties. The cultivars with the lowest reducing sugar contents, ATX 854 04-8W (0.03%) and NDTX 4930-5W (0.08%), were the ones that produced potato chips with the lowest acrylamide content. Based on these results, we cannot say that there is a correlation between reducing sugar and acrylamide formation. More experiments need to be done to exactly determine the amount of reducing sugar and potato variety.

It was not surprising to note that the potato chips with the greatest acrylamide content (regardless of frying method used) were obtained from the White-rose potatoes, a variety that is mostly used for boiling and baking and is unsuitable for chipping (Table 1). On the other hand, Shepody, a cultivar that is also not suitable for chipping, produced potato chips with intermediate acrylamide contents (537 ppb) under traditional frying but considerably lower acrylamide values during vacuum frying (38 ppb). The difference in acrylamide contents between these 2 cultivars was probably the lower reducing sugar content of the Shepody cultivar (0.18%).

The variety ATX847806-2Ru produced chips with high acrylamide content under atmospheric frying (1554 ppb) but performed well under vacuum frying (44 ppb). Generally, russet-type potatoes are very good for boiling and baking and excellent for french frying. The varieties that performed the best, in terms of acrylamide formation, were those whose use is strictly for chipping (NDTX 4930-5W and ATX 854 04-8W).

Figure 2 shows the effect of frying time on the acrylamide content of potato chips. The potato variety used was Atlantic. Acrylamide content increased with frying time and was significantly affected by the frying method used (Figure 2, 7, and 8). During vacuum frying, there was a slight increase in acrylamide content as frying time increased. The final moisture contents were 1.3% ± 0.1% (wb) and 1.2% ± 0.1% (wb) for the chips fried with traditional and vacuum frying, respectively.

Chip colors prepared from different potation variety

Figure 3 shows the color L and b values of the different potato

Table 4—Statistical analysis for the effect of potato cultivars on the product quality attributes (PQA)[a]

Frying methods	Traditional			Vacuum		
Cultivar	Acrylamide (ppb)	Color (b)	Texture (N)	Acrylamide (ppb)	Color (b)	Texture (N)
Innovator	551.646D,a	16.263C,a	2.912C,a	35.354BC,b	15.088F,b	2.467B,a
NDTX4930-5W	358.478A,a	14.757A,a	2.287AB,a	0.00A,b	8.288A,b	2.012A,a
ATX85404-8W	397.516AB,a	15.497B,a	2.625ABC,a	25.387B,b	10.589AD,b	2.520AB,a
Atlantic	466.312BC,a	15.164AB,a	2.104A,a	74.710D,b	10.151BC,b	2.939B,a
Shepody	536.498CD,a	16.495CD,a	2.693BC,a	37.823BC,b	9.709B,b	2.790B,a
ATX847806-2Ru	1554.460E,a	17.245E,a	2.341AB,a	43.726C,b	10.135BC,b	2.427AB,a
White-Rose	3891.600F,a	12.975F,a	3.044D,a	243.599E,b	12.382E,b	3.882C,a

[a]Means followed by the same letter are not significantly different ($P < 0.05$). Uppercase letters (A–F) refer to effect of potato varieties' lowercase letters (a–b) refers to effect of frying methods.

chips fried under traditional and vacuum frying conditions. The *a* values (not shown) of the potato chips fried with both methods were negative, indicating a tendency of the potato chips to have more of a greenish color rather than red. A red color is an indication of overcooked potato chips. The White-rose variety produced chips with the highest *a* value (and positive). The vacuum frying produced potato chips with lower *a* values than the traditional fryer for varieties Innovator, NDTX 4930-5W, ATX 854 04-8W, and White-Rose; the other varieties, Atlantic, Shepody, and ATX847806-2Ru, showed no difference in the values of *a* for both frying conditions.

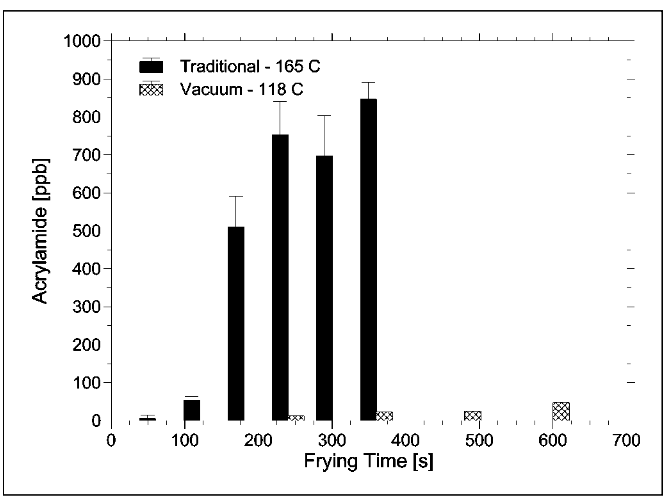

Figure 2—Effect of frying time on the acrylamide content of Atlantic variety fried in a traditional deep-fat fryer (165 °C) and a vacuum fryer (118 °C)

The *L* value describes lightness and is equal to zero for black and 100 for white. This corresponds to the intensity of light recorded by the human eye. The values of *L* changed slightly for all varieties. Most of the time, the traditional frying system produced chips that were lighter in color with greater *L* values than the chips that were vacuum fried. ATX 854 04-8W was the only variety that produced chips with similar *L* values for both traditional and vacuum frying conditions. The White-rose variety, on the other hand, produced chips with different *L* values, that is, 38.3 (darker chips) and 46.2 (lighter chips) for the traditional and vacuum systems, respectively.

The *b* value measures the yellow-blue chromaticity of the sample (–120 to 120). The statistical analysis showed significant differences ($P < 0.05$) for *b* values as a function of varieties for both frying conditions (Table 4). However, the potato chips processed under vacuum frying were significantly lower in *b* values ($P < 0.05$) than the chips fried under the traditional conditions.

Figure 4 shows the effect of time on the color (value *b*) of potato chips (Atlantic variety) processed under atmospheric and vacuum conditions. The potato chips fried under vacuum had lower *b* values than the chips fried under the traditional method. There was a

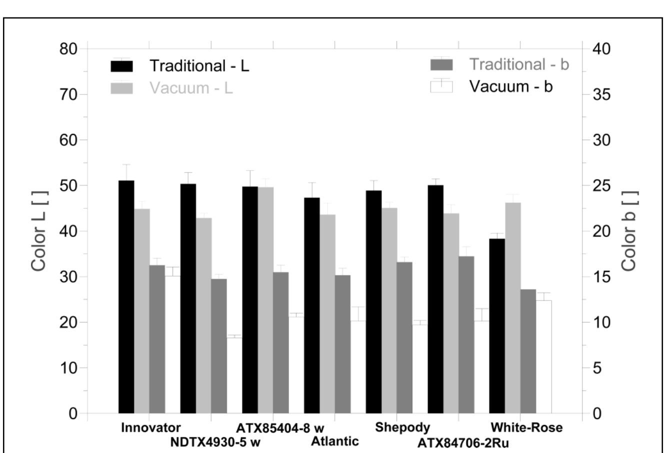

Figure 3—Color values (*L* and *b*) for different potato varieties fried in a traditional deep-fat fryer (4 min at 165 °C) and a vacuum fryer (8 min at 118 °C)

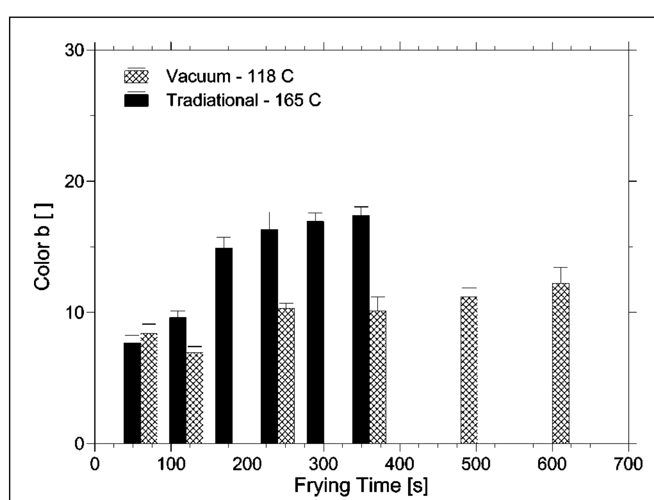

Figure 4—Effect of frying time on the color values (*b*) of Atlantic variety fried in a traditional deep-fat fryer (165 °C) and a vacuum fryer (118 °C)

slight increase in the *b* values during time for both frying conditions.

In summary, we can say that vacuum frying can produce potato chips with low acrylamide content and desirable color attributes. The frying temperature/time combinations yielded potato chips with desirable color attributes as indicated by the lightness and chromaticity values.

Chip textures prepared from different potato varieties

Figure 5 shows that there was small effect ($P < 0.05$) of the potato variety on the texture of the potato chips, and the statistical analysis showed no significant differences for texture values as a function of varieties for both frying conditions (Table 4).

When comparing the texture of potato chips produced from the Atlantic variety fried at different times (Figure 6), no significant differences ($P < 0.05$) were found between the potatoes produced by the 2 different frying methods (Table 4).

Therefore, vacuum frying can produce low acrylamide potato chips with the same texture characteristics of those obtained under the traditional frying method.

It is important to mention that the flavor characteristics (mouth feel, flavor) of the chips fried under vacuum fryer were not different from those processed under the traditional (atmospheric) fryer.

Acrylamide in chips fried in different temperatures

Figure 7 shows the effect of frying temperatures (150 °C, 165 °C, and 180 °C) on the acrylamide formation in potato chips (Atlantic variety) fried for a maximum of 6 min in a traditional fryer. Acryla-

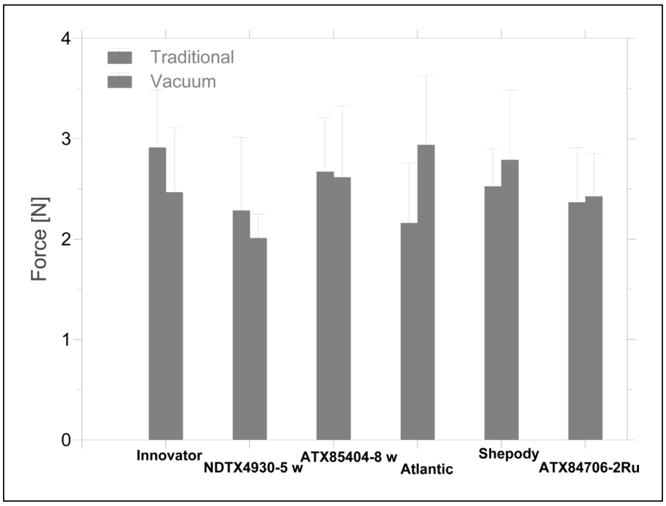

Figure 5—Texture (force to break) values for different potato varieties fried in a traditional deep-fat fryer (4 min at 165 °C) and in a vacuum fryer (8 min at 118 °C)

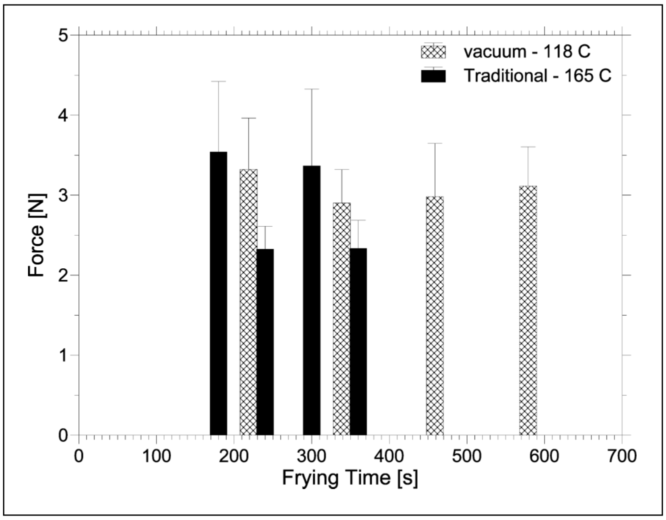

Figure 6—Effect of frying time on the texture (force to break) of Atlantic variety fried in a traditional deep-fat fryer (165 °C) and in a vacuum fryer (118 °C)

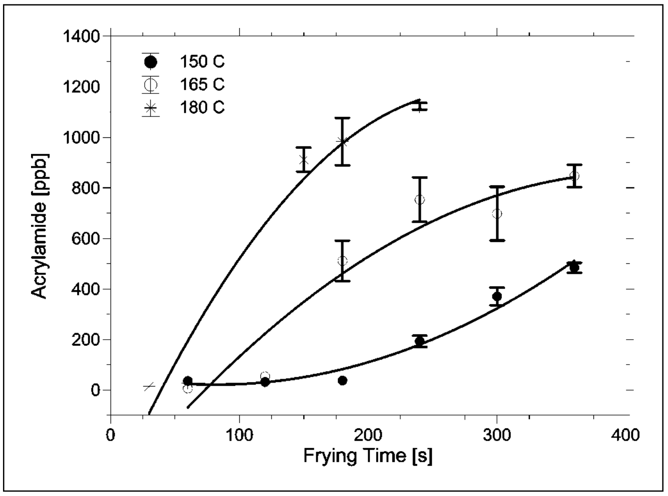

Figure 7—Effect of frying temperature on the acrylamide content (ppb) of potato chips (Atlantic variety) fried under atmospheric frying conditions. The solid lines correspond to a 2nd-order polynomial fit: 180 °C = acrylamide [ppb] = –416 + 11.38t – 0.02025t²; 165 °C = acrylamide [ppb] = –416.6 + 6.25t – 0.007651t²; 150 °C = acrylamide [ppb] = 63.4 - 1.032t + 0.006323t²

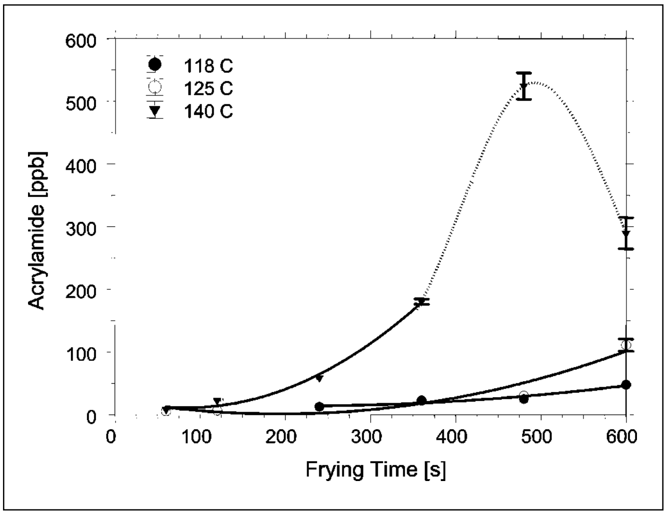

Figure 8—Effect of frying temperature on the acrylamide content (ppb) of potato chips (Atlantic variety) fried under vacuum frying conditions. The solid lines correspond to a 2nd-order polynomial fit: 140 °C = acrylamide [ppb] = 27.3 – 0.38t – 0.0022t²; 125 °C = acrylamide [ppb] = 23.8 – 0.23t + 0.00061t²; 118 °C = acrylamide [ppb] = 24.2 – 0.094t + 0.00022t²

mide content increased significantly with frying time for all frying temperatures. The rate of acrylamide formation increased with temperature, and it was greatest (about 6.06 ppb/s on average) for the potato chips fried at 180 °C. At 150 °C, the concentration of acrylamide content did not change significantly during the first 180 s of frying (around 37 ppb) and then increased steadily (at rate of 1.63 ppb/s in average) to a value of approximately 484 ppb after 360 s of frying. The final moisture content for the chips were as follows: 1.8% ± 0.3% (wb) (150 °C); 0.98% ± 0.1% (wb) (165 °C); 0.45% ± 0.03% (180 °C). The chips were overfried by 120 s when fried at 165 °C and by 60 s at 180 °C to illustrate the effect of frying time/temperature on the acrylamide formation of potato chips fried in the traditional fryer.

When frying the chips to the same final moisture content (1.5% ± 0.3% wb), the reduction of frying temperature from 180 °C to165 °C, from 165 °C to 150 °C, and from 180 °C to 150 °C, decreased the acrylamide content by about 23%, about 36%, and about 51%, respectively. When lowering the oil temperature from 190 °C (not shown) to 165 °C and to 150 °C, the reductions in acrylamide content were 63% and 76%, as reported by Pedreschi and others (2004) and Haase and others (2003), respectively.

The effect of temperature of the acrylamide formation was less dramatic for vacuum frying (Figure 8) because of the lower frying temperatures used. For potato chips fried at 118 °C and 125 °C, the acrylamide formation rate was very low (ranging from 0.02 to 0.08 ppb/s) during the first 480 s of frying. After 600 s of frying, the acrylamide content increased from approximately 25 to 48 ppb at the frying temperature of 118 °C and from 30 to 112 ppb at 125 °C. However, for the frying temperature of 140 °C, acrylamide formation was favored as frying time increased, reaching a maximum at 480 s (about 524 ppb). At 600 s of frying, though, acrylamide formation was reduced by about 2 times the amount formed at 480 s. The chips fried at 140 °C were over-fried by 240 s to demonstrate the effect of time-temperature effects on the acrylamide rate during vacuum frying.

The reduction of the frying temperature from 140 °C to125 °C decreased the acrylamide content by 63%, from 125 °C to118 °C by only 10% and from 140 °C to 118 °C by 56%, when frying the chips to a final moisture content of (1.6% ± 0.2% wb).

Conclusions

This study showed that acrylamide content in potato chips is affected by potato cultivars. Selection of chipping potato cultivars with low reducing sugar would greatly reduce the acrylamide content in potato chips. Compared with traditional frying (atmospheric conditions), vacuum frying reduced acrylamide formation in potato chips dramatically by about 94%. Vacuum frying potato slices at 118 °C produced potato chips with low acrylamide content and desirable yellow golden color and texture attributes compared with those fried in the traditional fryer. The frying oil temperature-time combination also affected acrylamide formation significantly in the potato chips. For the 2 treatments studied, acrylamide formation decreased significantly in potato chips as the frying temperature decreased from 180 °C to 150 °C for the traditional method and from 140 °C to 118 °C for the vacuum frying.

Acknowledgments

The authors would like to thank Dr. J. C. Miller, Jr. (Horticulture, Texas A&M Univ.) for providing the potato cultivars and Dr. Larry Dangott (Biotechnology, Texas A&M Univ.) for technical assistance with the acrylamide analysis.

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