

Acrylamide and Oil Reduction in Fried Potatoes: A Review

Franco Pedreschi* • Rommy N. Zuñiga**

Pontificia Universidad Católica de Chile, Departamento de Ingeniería Química y Bioprocesos, Av. Vicuña Mackena 4860, P.O. Box 306, Santiago, Chile *Corresponding author:* * fpedreschi@ing.puc.cl ** rnzuniga@uc.cl

ABSTRACT

Potato is the raw food material that has been used the most in frying operations due to the high demand of consumers all over the world. Detection of high concentrations of acrylamide in heated starch rich foodstuffs, such as potato, by the Swedish National Food Administration in April 2002 attained public concern because this product is a suspected human carcinogen. Maillard reaction is suggested as the major mechanism of acrylamide formation in fried potatoes. The precursors of this reaction for fried potatoes are glucose, fructose and asparagine. So, several methods based in diminishing or eliminating acrylamide precursors have been implemented. On the, other hand, other reduction methods of acrylamide focus principally in the process parameters such as vacuum frying or conventional frying at low temperatures. Post-frying techniques could eventually be implemented to diminish acrylamide formation as well. But the major challenge is to reduce as much as possible acrylamide levels in fried potatoes but maintaining intact their sensorial properties and low oil content. Typical final oil content of potato chips and French fries are ~35% and ~15% by weight, respectively. Some of the principal factors that affect oil absorption in fried potato products are process parameters (temperature, pressure and frying time), deterioration degree of the frying oil, food geometry and pre-treatments (e.g. drying, solute impregnation, edible film coatings). Recently, much attention has been given to the use of vacuum frying which may be an option to produce fried potatoes with low oil content. Reducing acrylamide and oil content while maintaining product quality (flavor, color, texture, safety, etc.) in commercial fried potato production is a crucial challenge for the food industry.

Keywords: acrylamide, French fries, frying, oil, potatoes, potato chips

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INTRODUCTION

Fried potatoes comprise a significant part of the western diet, and their importance is most likely to continue. For decades, consumers have desired fried foods because of their unique flavor-texture combination. However, increasing consumer awareness of the relationship between nutrition and health has become a driving force for reducing oil consumption (Dana and Saguy 2006). Besides, recently reports of the presence of acrylamide in fried potatoes have caused worldwide concern. Acrylamide is a known carcinogen substance in experimental animals that occurs in carbohydrate-rich foods as a result of cooking methods at high temperatures. Acrylamide has been classified as probably carcinogenic in humans. So, for potato industry it is not only important to know the principal mechanism(s) of acrylamide formation in fried potatoes but also several acrylamide mitigation procedures reported in the literature that could be very useful for fried potato manufacturers in order in reduce to reasonable levels the acrylamide generation in their processing lines. For instance, it is very important to select the proper potato tuber for frying. The potential capability of different potato varieties to form acrylamide during heat treatment correlated well with the concentration in the tubers of reducing sugars (especially glucose and fructose) and asparagine. The amount of sugars and asparagine in potato tubers is influenced by different factors such as: potato cultivar, fertilizers, climate, storage conditions, etc.

Fried potatoes contain significant amounts of oil at the end of frying, with values of \sim 35% and \sim 15% by weight for potato chips and French fries, respectively (Aguilera and Gloria-Hernandez 2000). The frying process uses fats and oils as a heat transfer medium (Mehta and Swinburn 2001). All edible fats and oils are water-insoluble substances that consist predominantly of glyceryl esters of fatty acids or triglycerides, with some nonglyceridic materials present in small or trace quantities. The terms fats and oils are used interchangeably, and the choice of terms is usually based on the physical state of the material at ambient temperature and tradition. Generally, fats appear solid at ambient temperatures and oils appear liquid (O'Brien 2004). Apart from palm oil, or its fractions, other popular vegetable oils used for chips and French fries frying are soybean, rapeseed and sunflower oils, usually hydrogenated in order to improve their thermo-oxidative stability (Kochhard 2001)

Controlling fat intake has been a consistent diet-related message since the late 1950's when the American Heart Association first recommended that dietary cholesterol, saturated fat, and total fat were reduced (Popkin et al. 2001). Especially over the last decade it has recognized the desirability of reducing fat content of deep-fat fried products. This is because saturated animal fats are the most important dietary factor contributing to the pathology of the cardiovascular diseases, obesity and diabetes (Minihane and Harland 2007). In most countries diseases associated with a high fat intake are a major health burden. Non-communicable chronic diseases such as coronary heart diseases, stroke, obesity, and diabetes mellitus are either common or increasing in almost every country. Besides, they are the major causes of mortality and morbility worldwide (Mehta and Swinburn 2001; Minihane and Harland 2007). Nowadays, all national dietary guidelines recommend low to moderate total fat intakes and low saturated fat intakes. As a consequence, consumer trends are moving toward healthier foods and low-fat products, creating the need to reduce the amount of oil in fried products.

Deep-fat frying is a complex process that involves heat and mass transfer mechanism and a variety of physical and chemical changes (Moreira *et al.* 1999). A better understanding of the mechanisms of acrylamide formation and oil uptake can help us to implementing acrylamide mitigation and oil reduction procedures for deep-fat fried potatoes. This review presents an overview of the mechanism of acrylamide formation and oil uptake. Moreover, existing procedures to reduce acrylamide generation and oil absorption are reviewed.

ACRYLAMIDE IN FRIED POTATOES

Acrylamide is an odorless and colorless crystalline solid with a melting point of 84.5° C that is formed from the hydration of acylonitrile. The observation that acrylamide used as a sealing adjuvant in tunnel construction in Sweden was responsible for adverse health effects in exposed workers led researchers to an association of acrylamide with foods. Before its discovery in foods, acrylamide was known as an industrial chemical and a component of cigarette smoke. Besides, recent epidemiological studies by the University of Maastricht supported by the Dutch Food Safety Agency indicate a positive association between dietary acrylamide and the risk of certain types of cancer (Hogervorst *et al.* 2007). These researchers have observed increased risks of endometrial and ovarian cancer with increasing dietary acrylamide intake, particularly among never smokers. Risk of breast cancer was not associated with acrylamide intake. Choosing a balanced and varied diet, and avoiding overcooking of certain starchy foods, will contribute to reducing dietary intake of acrylamide.

Besides, increased dietary intakes of acrylamide could raise the risk of kidney cancer by 59%, says a new study from the Netherlands (Hogervorst et al. 2008). Contradiction have been reported between observational studies and those of animal studies, where high acrylamide doses led to increased rates of cancer of the thyroid, testicles, breasts, and uterus, has been suggested to be due to excessive exposure of the animals to the chemical – the animal studies used does 1,000 to 100,000 times higher than what humans are exposed to, and the animal studies provided the acrylamide from water, unlike humans who obtain acrylamide from food sources. Scientists have also suggests that humans may effectively detoxify acrylamide when consumed at dietary levels. Despite the inconsistency in the literature, industry and universities are actively exploring effective ways of reducing the formation of acrylamide. Moreover, acrylamide-reducing ingredients are already commercially available.

In April 2002, Swedish researchers shocked the food safety world when they presented preliminary findings of acrylamide in some fried and baked foods, most notably potato chips and French fries. They attributed this fact to the higher temperatures reached in Maillard nonenzymatic browning reactions required for desirable color, flavor and aroma production in those cooking operations. Some authors have shown that acrylamide was formed by heating above 120°C certain starch-based foods, such as potato chips and French fries which can exhibit relatively high values of acrylamide such as 424 and 1739 μ g/kg, respectively (Rosen and Hellenäs 2002; Tareke *et al.* 2002).

Variables that can affect acrylamide formation in fried potato are: concentration of acrylamide precursors in raw potato (reducing sugars and asparagine), cut potato surface area and shape, cooking temperature and time, and other processing conditions. There are two basic ways to reduce acrylamide in fried potatoes:

• Through the raw material itself, the potato.

• Through influencing the technology used in the production of fried potatoes.

Some of the measures introduce by the industry are:

(a) To optimize the temperature/profile during the deepfrying process.

(b) To increase end-product moistness.

(c) To use opto-electronic sorting process to remove dark fried potatoes.

Finally, the analytical methods for acrylamide determination relies on using (i) gas chromatography and mass spectrometry, GC-MS (Tareke *et al.* 2002), (ii) liquid chromatography and tandem mass spectrometry, LC-MS-MS (Rosen and Hellenäs 2002). Granby and Fagt (2004) validated an analytical method for analyzing acrylamide in coffee. Recently, a liquid chromatography-tandem mass spectrometry analytical methodology for simultaneous analysis of acrylamide and their precursors such as asparagine and glucose was implemented with a detection limit for acrylamide of 20 μ g/kg for French fry analysis (Nielsen *et al.* 2006).

MECHANISMS OF ACRYLAMIDE FORMATION

Reports of the presence of acrylamide in fried potatoes have caused worldwide concern because this compound has been classified as probably carcinogenic in humans with significant toxicological effects namely neurotoxic and mutagenic. Acrylamide is a suspected carcinogen that is formed during by heat-induced reaction between sugar and an amino acid called asparagine (Rosen and Hellenäs 2002; Mottram *et al.* 2002; Stadler *et al.* 2002; Pedreschi *et al.* 2005a). For instance, Mottram *et al.* (2002) showed how acrylamide could be formed from food components during heat treatment as a result of the Maillard reaction between amino acids and reducing sugars. On the other hand, Stadler *et al.* (2002) have shown also that acrylamide can be released by the thermal treatment of certain amino acids such as asparagine, particularly in combination with reducing sugars, and of early Maillard reaction products (N-glycosides).

Known as the Maillard reaction, this process is responsible for the brown color and tasty flavor of baked, fried and toasted foods. So, producing French fries or potato chips with no or low levels of acrylamide without affecting the sensorial properties of the final product is a major challenge for fried potato manufacturers (Zhang and Zhang 2007). Besides, since the Maillard reaction is the principal mechanism of acrylamide formation in fried potatoes, most of the methods which attend to mitigate its formation tend to remove acrylamide precursors from raw potatoes (such as glucose and fructose, and asparagine) or by different process modifications to inhibit or reduce the intensity of Maillard reaction. As acrylamide has not been detected in unheated or boiled foods, it was considered to be formed during heating at high temperatures. They attributed this fact to the higher temperatures reached in Maillard nonenzymatic browning reactions required for desirable color, flavor and aroma production, specially in the surface of fried potatoes (Coughlin 2003). For instance, Tareke et al. (2002) showed that acrylamide was formed by heating above 120°C certain starch-based foods, such as potato chips, French fries, bread and processed cereals.

Additionally, both potato variety and field site (fertilization and storage conditions) had a noticeable influence upon acrylamide formation since they affect acrylamide precursor concentrations in the tubers. In addition to potato tuber composition, other factors involved in acrylamide formation are the processing conditions (pre-treatments, temperatures and times of frying, type of frying and post-frying treatments). The potential capability of different potato varieties to form acrylamide during heat treatment correlated well with the concentration in the tubers of reducing sugars (especially glucose and fructose) and asparagine. The potato cultivars show large differences in their potential to form acrylamide which was primarily linked to their sugar contents (Amrein et al. 2003). Finally, some studies to date clearly show that asparagine is mainly responsible for acrylamide formation in heated foods after condensation with reducing sugars or a carbonyl source (Gökmen and Palakzağlu 2008). Moreover, the sugar asparaginase adduct, Nglycosylasparagine, generates high amounts of acrylamide, suggesting the early Maillard reaction as a major source of acrylamide (Stadler et al. 2005). Additionally, decarboxylated asparagine (3-aminopropionamide), when heated, can generate acrylamide in the absence of reducing sugars (Zyzak et al. 2003).

MECHANISMS OF ACRYLAMIDE MITIGATION

Awareness of acrylamide's presence stems from a 2002 study conducted by Swedish National Food Authorities, which identified high levels in some bakery and snack products. Since then acrylamide reduction has been a major target for food manufacturers, but efforts to address it by reducing heat have impaired the sensory properties of finished products (Mestdagh et al. 2005). Reducing acrylamide levels while maintaining product quality (flavor, color, texture, safety, etc.) in commercial fried potato production is a crucial challenge. Some strategies at different levels of production have been reported by Hanley et al. (2005) to mitigate acrylamide formation in fried potatoes: (i) Prevention of acrylamide formation by acrylamide removal of the essential precursors (asparagine and a source of a carbonyl moiety -generally a reducing sugar-); (ii) Interruption of the reaction by the addition of chemically reactive compounds that are able to react with intermediates in the Maillard reaction; (iii) Removal of acrylamide after it has been formed; (iv) Minimize acrylamide formation by changing frying

conditions (frying, pressure, time, etc). Among the variables that can affect acrylamide formation in fried potato are: glucose and asparagine concentrations, cut potato surface area and shape, cooking temperature and time, and other processing conditions. So, frying oil type (canola, cotton, seed, olive, peanut, shortening, soybean and sunflower) per se is not an important variable for acrylamide formation, with the exception of olive oil which increase significantly acrylamide generation (Mestdagh et al. 2005). Many additives have found to have the inhibitory effect of acrylamide formation in the Maillard reaction (Zhang and Zhang 2007). Acrylamide formed in the Maillard reaction may also be reduced via the addition of exogenous chemical additives, which should comply with the following conditions: (i) The addition level should be properly controlled according to corresponding criteria of food additives; (ii) The selected additives should be non toxic; (iii) The additives can not affect the sensorial properties of the fried potatoes. Some potato relevant tissue pre-treatments to reduce acrylamide formation during frying will be explained next.

Asparaginase pre-treatment

Acrylamide elimination could also be achieved via the use of asparaginase (Hendriksen *et al.* 2005; Cieserova *et al.* 2006; Pedreschi *et al.* 2008a). Aspaginase demonstrated to be an effective tool at reducing the formation of acrylamide in fried potatoes. Asparaginase converts free asparagine into aspartic acid, another animo acid that does not form acrylamide while the nutritional properties are unaffected, and nor are the browning and taste aspects.

Ciesarová *et al.* (2006) found that an important mitigation of acrylamide formation (90-97%) could be achieved also in products prepared from dried potato powder treated by L-asparaginase. On the other hand, using the asparaginase enzyme to treat French fries could reduce the formation of acrylamide by 60%, a joint Chilean-Danish study has reported. Asparaginase just right now is commercially available and it can be reused in many batches. This fact will bring down enzyme dosage per kg final product, and thereby also costs. The content of asparaginase in the solution is low meaning that the total protein load of the water



Fig. 1 Acrylamide content of blanched French fries treated with asparaginase. BDPF: Blanched potato strips at 75°C for 10 min, dried at 85°C per 10 min, partially fried at 175 °C for 1 min, frozen at -30°C for 2 days and finally fried at 175°C for 3 min; BE1DPF: Blanched potato strips at 75°C for 10 min, immersed in an 10,000 ANSU/L asparaginase solution at 40°C for 20 min, dried at 85°C for 10 min, partially fried at 170°C for 1 min, frozen at -30°C for 2 days and finally fried at 175°C for 3 min; BE2DPF: Blanched potato strips at 75°C for 10 min, immersed in an 10,000 ANSU/L asparaginase solution at 50°C for 10 min, dried at 85°C for 10 min, partially fried at 175°C for 1 min, frozen at -30°C for 2 days and finally fried at 175°C for 3 min; BE3DPF: Blanched potato strips at 75°C for 10 min, immersed in an 10,000 ANSU/L asparaginase solution at 60°C for 10 min, dried at 85°C for 10 min, partially fried at 175°C for 1 min, frozen at -30°C for 2 days and finally fried at 175°C for 3 min. Reprinted from Pedreschi F, Kaack K, Granby K (2008a) The effect of asparaginase on acrylamide formation in French fries. Food Chemistry 109, 386-392, with kind permission from Elsevier, ©2008.



Fig. 2 Effect of asparaginase over (A) glucose and (B) asparagine content of potato strips before drying, par-frying and final frying. C: Control or raw potato strips; B: Blanched potato strips at 75°C for 10 min; BE1: Blanched potato strips at 75°C for 10 min and then immersed in an 10000 ANSU/L asparaginase solution at 40°C for 20 min; BE2: Blanched potato strips at 75°C for 10 min and then immersed in an 10000 ANSU/L asparaginase solution at 40°C for 20 min; BE2: Blanched potato strips at 75°C for 10 min and then immersed in an 10000 ANSU/L asparaginase solution at 50°C for 10 min; BE3: Blanched potato strips at 75°C for 10 min and then immersed in an 10000 ANSU/L asparaginase solution at 60°C for 10 min. Reprinted from **Pedreschi F, Kaack K, Granby K** (2008a) The effect of asparaginase on acrylamide formation in French fries. *Food Chemistry* **109**, 386-392, with kind permission from Elsevier, ©2008.

will not affect the overall quality of the process waste water.

In 2008, Pedreschi, in collaboration with researchers from the University of Aarhus (Denmark), and the Technical University of Denmark, reports that treating the control strips with the solution reduced acrylamide formation in ~62% (Fig. 1) (Pedreschi et al. 2008a). The authors concluded that soaking of blanched potato strips (75°C, 10 min) in an 10,000 ASNU/l asparaginase solution at 40°C for 20 min is an effective way to reduce acrylamide formation after frying by reducing the amount of one of its important precursors such as asparagine. Fig. 2A shows that neither the blanching pre-treatment (75°C, 10 min) nor the asparaginase soaking pre-treatments had a considerable effect in removing glucose, an important precursor of acrylamide formation during frying. On the other hand, the asparaginase soaking pre-treatment had a significant effect in removing asparagine (P < 0.05), another important precursor of acrylamide formation during frying (Fig. 2B).

Soaking pre-treatment

On the other hand, levels of reducing sugars can be lowered by soaking the cut potatoes in water at room temperature before they are fried. Pedreschi *et al.* (2004) showed that glucose content in potato slices decreased slightly as the soaking time in water increased due to the water extraction of this component (**Fig. 3**). On the other hand, asparagine content tended to remain constant even for 90 min of soaking time (**Fig. 4**). When comparing the control (no soaking in water) with samples soaked in water for 40 and 90 min, the decrease in glucose content was 25 and 32%, respectively, while asparagine content remained almost constant in



Fig. 3 Glucose content of potato slices soaked 0 min (control), 40 min and 90 min in distilled water before frying. Reprinted from Pedreschi F, Kaack K, Granby K (2004) Reduction of acrylamide formation in fried potato slices. *Lebensmittel Wissenschaft und Technologie* **37**, 679-685, with kind permission from Elsevier, ©2004.



Fig. 4 Asparagine content of potato slices soaked 0 (control), 40 and 90 min in distilled water before frying. Reprinted from Pedreschi F, Kaack K, Granby K (2004) Reduction of acrylamide formation in fried potato slices. *Lebensmittel Wissenschaft und Technologie* 37, 679-685, with kind permission from Elsevier, ©2004.



Fig. 5 Acrylamide content of potato slices soaked 0 min (control), 40 min and 90 min in distilled water after being fried at 150, 170 and 190°C. Reprinted from Pedreschi F, Kaack K, Granby K (2004) Reduction of acrylamide formation in fried potato slices. *Lebensmittel-Wissenschaft und-Technologie* 37, 679-685, with kind permission from Elsevier, ©2004.

 9.95 ± 0.99 g/kg dry basis. Both the fried control and soaked samples, showed a marked increase in acrylamide formation as the frying temperature increased from 150 to 190°C (**Fig. 5**). For the three temperatures tested, acrylamide formation was higher in the control than in soaked samples suggesting that the soaking process leads to a higher leaching of one important acrylamide precursor such as glucose that finally results in lower acrylamide formation.

Blanching pre-treatment

Blanching serves a variety of functions, one of the main ones being to destroy enzymatic activity in vegetables and some fruits, prior to further processing. Potato blanching is



Fig. 6 Glucose content of potato strips blanched in hot water at different temperature-time combinations before frying. Control corresponds to unblanched potato strips. First numbers inside parenthesis indicate the blanching temperature (°C); second numbers indicate the blanching time (min). Reprinted from **Pedreschi F, Kaack K, Granby K, Troncoso E** (2007a) Acrylamide reduction under different pre-treatments in French fries. *Journal of Food Engineering* **79**, 1287-1294, with kind permission of Elsevier, ©2007.



Fig. 7 Asparagine content of potato strips blanched in hot water at different temperature-time combinations before frying. First numbers inside parenthesis indicate the blanching temperature (°C); second numbers indicate the blanching time (min). Reprinted from Pedreschi F, Kaack K, Granby K, Troncoso E (2007a) Acrylamide reduction under different pre-treatments in French fries. *Journal of Food Engineering* **79**, 1287-1294, with kind permission of Elsevier, ©2007.



Fig. 8 Acrylamide content of potato strips blanched at different temperature-time combinations after being fried at 150, 170 and 190°C. First numbers inside parenthesis indicate the blanching temperature (°C); second numbers indicate the blanching time (min). Control corresponds to unblanched potato strips. Reprinted from Pedreschi F, Kaack K, Granby K, Troncoso E (2007a) Acrylamide reduction under different pre-treatments in French fries. *Journal of Food Engineering* **79**, 1287-1294, with kind permission of Elsevier, ©2007.

a processing step whereby potatoes are heated either in steam or water for 2 to 3 min. This inactivates enzymes and prolongs the storage life of frozen chips. Blanching is performed when the reducing sugar level of the raw potatoes is high and could lead to undesirable dark color after frying (Andersson 1994).

Unlike soaking (which is usually done at ambient temperature), during blanching, potato pieces are immersed in water at temperatures $\geq 50^{\circ}$ C and some important changes could take place such as enzyme inactivation, partial starch swelling, etc. Levels of reducing sugars and asparagine can be lowered by blanching the cut potatoes in hot or warm water before they are fried. The longer the blanching time the lower acrylamide formation after frying, and the lower glucose and asparagine content in potato strips before frying. Not only glucose but also asparagine content (**Fig. 6** and 7, respectively) decreased drastically as the temperature and time of blanching increased leading to French fries with less acrylamide content after frying (Pedreschi *et al.* 2007a). Blanching lead to a significant reduction of acrylamide formation in potato strips after frying at the three frying temperatures tested (**Fig. 8**).

Salt solution pre-treatment

Water activity at the surface of the potato piece influences the mechanism of acrylamide formation during frying. One possibility to decrease water activity was to increase the local salt concentration. Pedreschi et al. (2008b) determined that blanching of potato slices (60°C for 30 min) in water and soaking in a 3 g/100 g of NaCl solution per 5 min at 25°C reduces acrylamide formation in potato chips fried at 170°C by almost 64% (Fig. 9A). Pre-drying of blanched potato slices until 60 g water/100 g (wet basis) before frying increased the formation of acrylamide at 170°C by ~68%. Soaking of blanched potato slices in the 3 g/100gNaCl solution for 5 min at 25°C, reduces by 11% acrylamide formation in potato chips after frying. However, when the slices are blanched directly in the 3 g/100 g of the NaCl solution at 60° C for 30 min, their acrylamide formation increased surprisingly by ~90%. On the other hand, blanched slices under the same conditions and fried at 190°C only have 10% acrylamide less than control slices fried at the



Fig. 9 Acrylamide content of potato chips fried at 170 °C for 5 min (A) and at 190 °C per 3.5 min (B). A: Control slices; B1: Slices blanched at 60°C for 30 min in water; B1C: Slices blanched at 60°C for 30 min in water and dried at 75°C until 60 g water/100 g (wet basis); B1D: Slices blanched at 60°C for 30 min in water and soaked in a 3 g/100 g of NaCl solution for 5 min at 25°C; B1D*: Slices blanched at 60°C for 30 min in a 3 g/100 g of NaCl solution. Reprinted from Pedreschi F, Kaack K, Granby K (2008b) Acrylamide generation in pre-treated potato chips. *Agro Food Industry hi-Tech* 19, 4-6, with kind permission of Teknoscienze, ©2008 (www.teknoscienze.com).

same temperature (Fig. 9B). Pre-drying in blanched slices increased acrylamide content by 27% when they were fried at 190°C. Soaking of blanched potato slices in the NaCl solution, reduced potato chip acrylamide formation by ~36% after frying at 190°C. However, when the blanching of the slices was made directly in the NaCl solution at 60°C per 30 min, the acrylamide content of the potato chips fried at 190°C increased by 80%. Frying at 190°C increased by 130% the acrylamide content (average value) of all the samples previously fried at 170°C.

Additionally, Gökmen and Senyuva (2007) showed that dipping of potato strips into calcium chloride solution inhibited the formation of acrylamide by up to 95% during frying. The sensory quality of the French fries in terms of golden yellow color and crispy texture, was not adversely affected by this pre-treatment. These authors found that at amounts equivalent to those of asparagine and fructose, added divalent cations such as Ca^{2+} were found to prevent acrylamide formation completely, whereas monovalent cations, such as Na⁺, almost halved the acrylamide formed.

Vacuum frying

Granda *et al.* (2004) studied alternative deep fat frying technologies such as vacuum frying as a potential methodology to reduce acrylamide in foods. These authors showed that that vacuum frying reduced acrylamide formation in potato chips by 94% in comparison to traditional frying. Since during vacuum frying water in potato pieces could evaporate at a temperature much lower than 100°C, temperature conditions for Maillard reaction formation are less favored leading to lower formation of acrylamide during frying. The highest the vacuum, the lower the acrylamide formation since water in potato will evaporate at lower temperatures. In addition, this new frying technique is able to produce fried products with lower oil content (see below).

OIL UPTAKE AND LOCATION IN FRIED POTATOES

Development of the oily and crispy dry surface is a major structural transformation occurring during frying of potatoes. During frying explosive evaporation lead to the formation of large pores. The voids left by removal of water through pores are then filled with oil, especially in the outer layer; this is the reason why oil uptake is determinate by the final moisture content of the food (Mehta and Swinburn 2001; Mellema 2003). However, oil absorption is expected to be product dependent. Crust formation, involving gelatinization of starch, softening of middle lamellae, dehydration and shrinkage of cells, provides the passages for oil migration into intercellular spaces (Pedreschi et al. 1999; Pedreschi and Aguilera 2002). There is abundant proof that oil hardly penetrates in the cooked core and that the microstructure of the crust (mean pore size, connectedness and permeability) is the main determining factor in oil uptake (Aguilera and Gloria 1997; Aguilera and Gloria-Hernandez 2000; Bouchon and Aguilera 2001; Bouchon et al. 2001).

Numerous studies have shown that most of the oil is confined to the surface region of the fried potatoes (Aguilera and Gloria 1997; Pedreschi et al. 1999; Bouchon et al. 2001; Pedreschi and Aguilera 2002; Bouchon et al. 2003). The greatest part of oil is retained in form of drops (50-100 µm in size) in the crust of the fried piece after the piece is fried and cooled (Aguilera and Gloria 1997). For French fries, Aguilera and Gloria (1997) found that crust contained ~6 times as much oil as the central core. Bouchon *et al.* (2001) showed, using infrared microspectroscopy, that oil penetration depth in potato is approximately 300-500 µm, which was very close to the evaporation front. Pedreschi et al. (1999) showed, using confocal laser scanning microscopy, that the oil seemed to flow through the passages that imposed the lowest resistance and was located in the intercellular spaces of the crust (Fig. 10) forming an "egg-box" structure around intact cells with no presence of oil in their



Fig. 10 Gallery of confocal images in fluorescence mode of oil distribution in a potato chip fried in oil mixed with NR (170°C, 3 min) observed at 20X (each square of the gallery is $640 \times 640 \mu$ m). Reprinted from Pedreschi F, Aguilera JM, Arbildua JJ (1999) CLSM study of oil location in fried potato slices. *Micoscopy and Analysis* 74, 33-34, with kind permission of John Wiley and Sons Ltd., ©1999.



Fig. 11 3-D resconstruction from the serial sections in Fig. 10 using Imaris software. Reprinted from Pedreschi F, Aguilera JM, Arbildua JJ (1999) CLSM study of oil location in fried potato slices. *Micoscopy and Analysis* 74, 33-34, with kind permission of John Wiley and Sons Ltd., ©1999.

interior (Fig. 11), which was later confirmed by Bouchon and Aguilera (2001) and Pedreschi *et al.* (2008c).

There is a little oil uptake into the fried product while it is immersed in the hot oil and steam is still escaping (Mehta and Swinburn 2001). Most of the oil in the fried piece surface does not penetrate during frying and it adheres to the piece surface at the end of the frying, and a high proportion of it penetrates into the food microstructure during post-frying (Ufheil and Escher 1996; Moreira et al. 1999; Bouchon et al. 2001, 2003). Several works have found that the majority of the oil uptake occurs after the food is removed from the oil (Ufheil and Escher 1996; Aguilera and Gloria-Hernandez 2000; Bouchon et al. 2003; Durán et al. 2007), as shown in Fig. 12. Bouchon et al. (2003) showed that only a small amount of oil (<5% of the total oil content) penetrates during frying because most of the oil was picked up at the end of the process, suggesting that oil uptake and water removal are not synchronous phenomena.

Oil uptake is essentially a surface-related phenomenon resulting from the competition between drainage along the surface and suction into the porous crust once the fried potato is removed from the oil and begins to cool (Bouchon *et al.* 2001). In fried potato cylinders, three different oil fractions can be identified as a consequence of the different absorption mechanisms (Bouchon *et al.* 2003):

• Structural oil, which represents the oil absorbed during frying.

• Penetrated surface oil, which represents the oil suctioned into the food during cooling after removal from



Fig. 12 Oil content distribution, structural oil content (SOC), surface oil content (SUOC) and total oil content (TOC) in blanched-NaCl impregnated potatoes chips during frying and cooling at 180°C. Reprinted from Durán M, Pedreschi F, Moyano P, Troncoso E (2007) Oil partition during frying and cooling. *Journal of Food Engineering* 81, 257-265, with kind permission of Elsevier, ©2007.



Fig. 13 Oil distribution in the final product (moisture content ~1.8%, total basis) fried at 120, 150 and 180°C. (A) Control; (B) blanched. TO: total oil; PSO: penetrated surface oil; SO: surface oil; STO: structural oil. Reprinted from Pedreschi F, Cocio C, Moyano P, Troncoso E (2008c) Oil distribution in potato slices during frying. *Journal of Food Engineering* 87, 200-212, with kind permission of Elsevier, ©2008.

the fryer.

• Surface oil, which is the oil that remains on the surface.

At the end of frying, surface oil represents only a minimal fraction (\sim 3%) of the total oil in the potato chips (**Fig. 13**) with no marked influence of frying temperature. Penetrated surface oil was the higher fraction of oil, ranged from 69 to 91% of the total oil. The higher the frying temperature, the higher the percentage of penetrates surface oil based on the total oil content (Pedreshi *et al.* 2008).

Some of the principal factors that affect oil absorption in fried products are: deterioration degree of the frying oil, temperature, pressure and frying time, food geometry, chemical composition of the raw food, pre-treatments, surface roughness and porosity of the food to be fried (Korikida *et al.* 2001; Saguy and Dana 2003).

On the other hand, high oil absorption in fried potato products has been related to a greater extent of deterioration (Aminlari *et al.* 2005) and a decrease of the sound emitted on fracturing the crispy food leading to a decrease in crispness perception of the product (van Vliet *et al.* 2007); however higher oil absorption increases the salt uptake of potato chips after frying due to an increase of adhesive forces (Buck and Barringer 2007).

MECHANISM OF OIL UPTAKE IN FRIED POTATOES

To obtain products low in fat, it is essential to understand the mechanisms involved during the frying process, so that oil migration into the structure can be minimized. According to Saguy and Dana (2003) and Dana and Saguy (2006) oil uptake can be described by the following two mechanism.

Water replacement

Changes in the cellular structure of potato product and the formation of pores due to water evaporation allow oil to penetrate into the voids created. As water turns into steam and escapes the product, it leaves behind a uniform sponge-like network (Saguy and Dana 2003). At a certain moment of frying the crust is dry and the flow of vapor (and hence the bubbling) stops. If the voids are quite large, there will be no resistance to the entering of oil. Under these circumstances oil can be taken up before the food is taken from the frying fat. This can for instance be the case for small food pieces like thin potato chips, for which the heating is more intense, and drying is completed earlier (Mellema 2003).

The water replacement mechanism is mainly related to large voids and cracks that typically characterize reformed and battered products (Dana and Saguy 2006). This mechanism offers a limited explanation for oil uptake in fried potatoes, since, as mentioned earlier, oil absorption occurs mainly during the cooling phase.

Absorption during the cooling phase

During frying, especially at high moisture content, moisture within the food is converted to steam, which escapes from the food through capillaries and channels in the cellular structure. Vapor creates an overpressure inside the pores; therefore oil cannot penetrate the food. This barrier of escaping steam continues until a few seconds after removal of the food from the oil (Mellema 2003; Saguy and Dana 2003). Then, food temperature drops leading to water vapor condensation and a subsequent decrease in internal pressure. Since most of the crust pores will be filled with vapor, and a film of oil will cover the surface of the fried food, oil will be driven into the pores due to the consequent "vacuum effect" (Mehta and Swinburn 2001; Mellema 2003; Saguy and Dana 2003; Dana and Saguy 2006). The decrease in temperature of the surface oil causes an increase in its viscosity, making it more difficult to the oil to drip off from the product surface (Moreira et al. 1999). As a result, oil will penetrate the crust using the pores, or "sponge voids" created by the evaporation (Mehta and Swinburn 2001; Mellema 2003; Saguy and Dana 2003; Dana and Saguy 2006).

It should be noted that the condensation mechanism is probably most important for short frying times and large food samples. The later is the case of French fries, where the final moisture content of the product is $\sim 38\%$ and at the end of frying bubbling still occurs (Mellema 2003).

Oil uptake is a dynamic complex process and the mechanisms described above comprise only a partial explanation and could not provide a complete description of the oil uptake phenomenon.

PROCEDURES OF OIL REDUCTION IN FRIED POTATOES

Because oil uptake is a surface phenomenon, the conditions after the fried potatoes are removed from the fryer seem decisive for oil uptake. The uptake of oil seems to be related to the adhesion of the oil onto the surface of the fried product, therefore, proper shaking and draining after frying are probably important deep-fat frying techniques for reducing the oil content of the products (Mehta and Swinburn 2001). Besides, several pre-frying procedures have been proposed to reduce the amount of absorbed oil in fried potatoes to make such products more acceptable to health-conscious consumer.

Effect of process conditions on oil absorption

The main process parameters influencing oil uptake are frying temperature and time. Oil absorption, generally, increases with frying time, but this trend is not linear. The effect of frying temperature over oil absorption is contradictory. It has been found that temperatures in the range between 155 and 185°C have no significant effect (Bouchon et al. 2003), although generally, increasing of frying temperature leads to a decreasing of oil uptake (Kita and Lisińska 2005; Pedreschi et al. 2005b; Moyano and Pedreschi 2006; Kita et al. 2007), possibly due to the reduced frying time necessary, formation of a better developed crust which would acts as a barrier for oil absorption, or by a reduction in the porosity o the crust. Kita et al. (2007) found that with every increase in frying temperature by 20°C, fat absorption was reduced by 3%, on average, with all the oils studied. On the other hand, several researchers (Alvarez et al. 2000; Gupta et al. 2000; Krokida et al. 2001) have reported an increase in oil content with frying temperature. Despite the effect of frying temperature over final oil content, higher frying temperatures produce an increase in the acrylamide content of fried products.

Many product variables such as food composition, product shape, surface to weight ratio and porosity affect the final fat/oil content of fried product. A linear relationship exists between the surface area and the oil content (Gamble and Rice 1988). Because oil absorption is a surface phenomenon, increasing the area/volume ratio of the product increase the oil uptake. Moreover, if the surface is rough, overall surface area increases and the result is an enlarged oil uptake.

Frying oil quality has also a certain influence on oil absorption and therefore on the organoleptic and nutritive characteristics of fried food products (Rimac-Brnčić *et al.* 2004). A number of reactions occur in the frying oil when potatoes are fried, causing oxidative and hydrolytic degradation and polymerization of the oil. Breakdown products of degraded oil are not a direct public health problem. However, degraded oil does increase oil absorption due to the prolonged frying time (Mehta and Swinburn 2001). Higher oil uptake during extended frying is probably related to increased oil viscosity caused by polymerization reactions taking place in the degrading oil, and not because formation of surface-active agents (Moreira *et al.* 1999; Dana and Saguy 2006).

It is worth mentioning that vacuum frying allows reducing oil content in fried potato (Garayo and Moreira 2002) as well as apple and carrot (Shyu *et al.* 2005; Mariscal and Bouchon 2008). In vacuum frying operations, the food is heated under reduced pressure in a closed system that can lower the boiling points of both the frying oil and the moisture in food. Garayo and Moreira (2002) showed that vacuum frying could produce potato chips with 30% less oil content than those fried in atmospheric fryers. Currently, fruit chips are produced at industrial level in batch type vacuum fryers, mainly in East-Asia countries. Also, continuous vacuum fryer equipments have been developed for large production of fried potatoes and fruits. Vacuum frying may be an option for production of fried potatoes with low acrylamide and oil content and the desired sensorial characteristics.

Blanching pre-treatment

As seen before, blanching in hot water can reduce the reducing sugars and asparagine levels (acrylamide precursors) of cut potatoes before frying. Also, blanching has been reported as a pre-treatment which could improve the color and texture of the chips and reduce their oil uptake by gelatinization of the surface (Califano and Calvelo 1987). However, it was found that blanched slices (85°C, 3.5 min) absorbed more oil than control slices after frying (Pedreschi and Moyano 2005a; Pedreschi et al. 2005b; Moyano and Pedreschi 2006; Pedreschi et al. 2008c). Fried control potato slices absorbed an average of 9% less oil than the corresponding blanched samples for the three temperatures tested, 120, 150 and 180°C (Fig. 14) (Pedreschi et al. 2005b). In agreement with these results, Alvarez et al. (2000) found that blanching for high temperatures and short times (97°C, 2 min), before frying of potato strips, resulted in higher oil content than in fresh strips, which is undesirable for the acceptance of the product by the consumer. On the other hand, some authors reported that low-temperature for longtimes blanching (55-70°C, 15-60 min) before frying activates pectinesterase enzyme and the resulting reactions decrease porosity and hence reduce oil uptake (Aguilar et al. 1997). Rimac-Brnčić et al. (2004) investigated the influence of blanching in water or water solutions of calcium chloride or citric acid on the oil absorption in fried potato strips. The samples blanched in water had the highest values for oil content, samples blanched in citric acid solution showed a slight reduction in oil content (13-15%) compared to samples blanched in calcium chloride solution (27-28%). The authors stated that calcium chloride is able to stabilize the tissue structure against the violence of the frying process by means of the reaction between calcium and native pectin of the potato tissue.

Drying pre-treatment

Drying is defined as the application of heat under controlled conditions to remove the majority of the water normally present in a food by evaporation. The main purpose of dehydration is to extend the shelf life of foods by a reduction in water activity (Fellows 2000). However, drying before frying is used to decrease the initial moisture content of potatoes (typically to a content of 60% wet basis), thus less amount of free moisture is available for removal during frying. In fact, the amount of water removed during the frying process determines the extent of crust formation, which defines the volume of the final oil reservoir.

Several studies show that decreasing the initial potato moisture content by air drying is an efficient way to reduce



Fig. 14 Final oil content in pre-treated potato chips (moisture content ~1.8%, total basis).

fat uptake in the final fried product (Gupta et al. 2000; Krokida et al. 2001; Pedreschi et al. 2005b; Pedreschi and Moyano 2005b; Moyano and Pedreschi 2006). The predrying decreased the oil content of French fries during frying, as the pre-drying time increases from 0 to 120 min, the oil content for the same frying time (20 min) decreases (Krokida et al. 2001). For temperatures of 120 and 150°C, it was found a decrease of around 20% in the oil content of pre-dried slices with respect to control slices, while at 180°C the decrease was only 6% (Fig. 14) (Pedreschi et al. 2005b). It is worth to mention that the high reduction potential of the drying pre-treatment is not due to a reduction of the moisture content on its own. The structural changes occurring at the surface of the piece, which generate an external crust with low permeability increases the resistance to oil absorption during frying, thus reducing oil uptake.

Solute impregnation pre-treatment

Osmotic dehydration is a method for the partial removal of water by immersion of food in concentrated solutions of soluble solids, without phase change. At the same time, the food also takes up solids from the osmotic solution. This method is used mainly for fruits and vegetables and produces a nonstable food with relatively high moisture content (Raoult-Wack 1994). Oil uptake is a surface phenomena and a simple way to change the surface properties of potato strips is by soaking them into a suitable solution, prior to frying, by a proper period of time. For the osmotic dehydration of potatoes, the more important fact is the solute impregnation onto the surface rather than the water loss before frying (Moyano and Berna 2002; Bunger *et al.* 2003).

Osmotic pre-treatment decreases the oil content of potato strips during frying in varying proportion, depending on the type of solution used (Krokida et al. 2001). For all the temperatures tested, salt soaking of blanched potato slices reduced oil absorption after frying, with values of 5, 3, 8 and 10% for 120, 140, 160 and 180°C, respectively (Pedreschi et al. 2007b). Potato strip impregnation in a 3% NaCl solution per 50 min allowed obtaining French fries with lower oil content ~22% (Fig. 15), crispier and with paler color than control (Bunger et al. 2003). During frying, solutes are concentrated on the surface, enhancing crust formation. The crust might be permeable to steam leaving the tissue but it might act as a barrier to oil uptake as well (Moyano and Berna 2002). Mai Tran et al. (2007) using pre-drying and subsequent dipping in a sugar solution 'sugar dipping') were able to produce a significant oil reduction (~30%) compared with control (no pre-dried, nondipping) or pre-dried and non-dipping samples. The sugar addition may induce a higher specific gravity or high solids thus leaving less space for oil uptake. The moisture contents of pre-dried and dipping samples were not different when compared with the other samples.



Fig. 15 Oil uptake (g oil/g dry matter) during frying and average oil uptake at 180°C. (□) soaked in NaCl solution (3% w/w, 50 min) sample, (♦) control sample. Reprinted from Bunger A, Moyano PC, Ríoseco VK (2003) NaCl soaking treatment for improving the quality of French-fried potatoes. *Food Research International* **36**, 161-166, with kind permission of Elsevier, ©2003.

Coating pre-treatment

As mentioned above, several pre-frying treatments intend to reduce the absorption by reducing surface permeability. This can be achieved through edible film coating using proteins and hydrocolloids, such as methylcellulose (MC), carboxymethyl cellulose (CMC), hydroxypropyl methylcellulose (HPMC), long fiber cellulose, corn zein, starch and modified starch, among others (Mellema 2003). Proteins and cellulose derivatives, including MC and HPMC are used in the frying process because exhibit thermo-gelation. The effectiveness of a coating is determined by its mechanical and barrier properties, which depend on its composition and microstructure, and by the characteristics of the substrate, as well (García et al. 2002). Mallikarjunan et al. (1997) stated that, in products coated with cellulose derivatives, a protective layer is formed on the surface of the samples during the initial stages of frying due to thermally induced gelation above 60°C. This protective layer inhibits the transfer of moisture and fat between the sample and the frying medium.

It was reported that some hydrocolloids, mainly cellulose derivatives, could reduce oil absorption during deep fat frying (García *et al.* 2002; Mellema 2003; García *et al.* 2004; Rimac-Brnčić *et al.* 2004). Rimac-Brnčić *et al.* (2004) fried potato strips coated with three commercial types of carboxymethyl cellulose derivatives, they showed that all three hydrocolloids were effective in decreasing oil absorption, with the highest effect being an oil reduction of 33–35% when comparing with the strips no coated. García *et al.* (2002, 2004) using a formulation of 1% MC and 0.5% sorbitol as plasticizer were able to produce an oil uptake reduction of 41% for potato strips. Also, the use of proteins as coatings has been studied; coating potato chips with sodium caseinate, whey protein concentrate and egg white proteins resulted in 14, 5 and 12.0% reduction in oil uptake, respectively (Aminlari *et al.* 2005).

CONCLUSIONS

Nowadays researchers have found more evidences related to toxicity of acrylamide in humans. The major challenge in frying of potatoes will be to achieve a substantial reduction of acrylamide while keeping desirable product attributes such as flavor and color (which are generated by similar Maillard reaction pathways). Among the pre-treatments mentioned to reduced acrylamide content, the use of asparaginase seems to be more effective in the changes in sensorial properties of the fried potatoes are minimal. Due to the increasing consumer awareness of the relationship between nutrition and health, oil reduction in fried products has become a subject of the uppermost importance in food frying research. A better understanding of the mechanisms of oil uptake can help to implementing oil reduction procedures for deep-fat fried potatoes. Hence, further research on the exact mechanism of oil absorption is needed. Several works has proved that oil absorption is a surface phenomenon. Most of the oil is confined to the surface region of the fried potatoes and the microstructure of the crust is the main determining factor in oil uptake. On this regard, drying as pre-frying treatment appears as a simple and effective technique to reduce oil content in fried potatoes. Vacuum frying may be an option for production of fried potatoes with both low acrylamide and oil contents. Reduction of acrylamide and oil content are major issues to consider in the production of fried potatoes (potato chips and French fries).

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