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A Farm-to-Fork Approach to Lower Acrylamide in Fried Potatoes

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ABSTRACT

Acrylamide is a probable human carcinogen, which is formed during frying or baking of carbohydrate-rich foodstuffs, such as potatoes. The presence of this heat-induced contaminant in a wide range of daily consumed foodstuffs sparked international research, focusing on analysis, occurrence and formation in food as well as on toxicological aspects. This review summarizes the state-of-the-art knowledge about the formation mechanisms of acrylamide and several key factors influencing its generation in fried potato products. Based on the knowledge gathered, suggestions are given to lower the acrylamide content in the final product as much as possible. For this, a farm-to-fork approach is followed starting from the agricultural practice, through several food-processing possibilities on industrial and home-cooking level. Furthermore, the dietary acrylamide exposure is investigated as well as the importance of canteen food.

Keywords: agriculture, catering, food contaminant, potato, precursors, processing, review
Abbreviations: 3-APA, 3-aminopropionamide; **MOE**, margin of exposure

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INTRODUCTION

The last decennia, increasing scientific knowledge and better detection techniques have revealed new possible human health risks. Acrylamide, a conjugated reactive molecule, is produced worldwide to synthesize polyacrylamide. This polymer has numerous applications, e.g. as grouting agent, as flocculant in wastewater treatment or in the cosmetic, paper or textile industries. Monomeric acrylamide is present in cigarette smoke or as residue in the polymer due to incomplete polymerization (Shipp *et al.* 2006). Because of a potential human exposure to monomeric acrylamide, numerous toxicological studies have been performed, demonstrating its carcinogenicity in animals and thus indicating potential human health risks. Therefore, acrylamide was considered as a probable human carcinogen already in 1994 (IARC 1994).

Besides its industrial use, acrylamide was discovered in a wide range of daily consumed foodstuffs (Rosén and Hellenäs 2002; Tareke *et al.* 2002). Typically, acrylamide was found in carbohydrate-rich products which are fried, baked or roasted at temperatures above approximately 120°C. **Fig. 1** shows the most recent European contamination data (Stadler and Scholz 2004; IRMM 2006). A large variability in acrylamide contamination can be observed within each food category. This variability was moreover found between different lots and even between different packaging units of the same lot, indicating that there are ways to reduce the degree of contamination (Dybing *et al.* 2005).

Fried potatoes (*Solanum tuberosum* L.), such as French fries and potato crisps, thus belong to the food category

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Invited Review

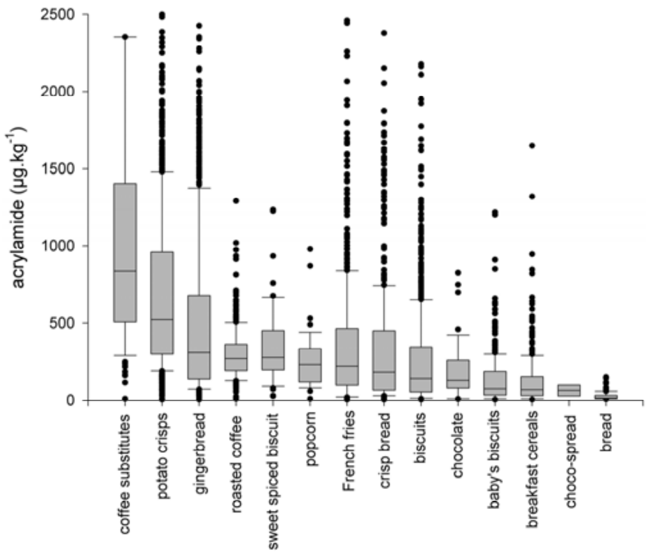

Fig. 1 Box plot diagram of acrylamide contamination data in the EU. Updated from Stadler and Scholz (2004); IRMM (2006).

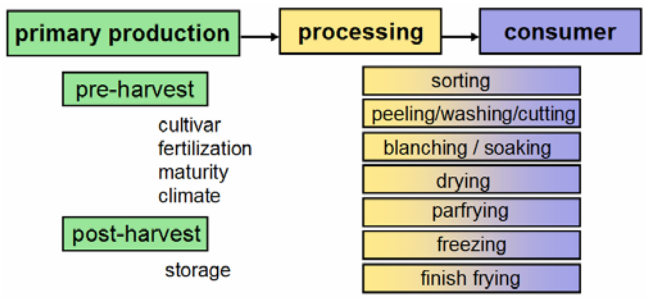

Fig. 2 Main steps in the manufacturing process of French fries, from farm to fork.

with a high acrylamide contamination level (Friedman 2003). As discussed below, these products are moreover frequently consumed. It is clear that these foodstuffs significantly contribute to the daily acrylamide exposure. Therefore, this review specifically focuses on the factors influencing the formation of acrylamide in these foodstuffs in order to reduce the dietary exposure as much as possible. Since every step in the production of fried potato products (shown in **Fig. 2**) may interfere with acrylamide formation, a farm-to-fork approach is indispensable.

DIETARY ACRYLAMIDE EXPOSURE AND HEALTH RISK

Many countries have estimated the dietary intake of acrylamide in order to evaluate the possible risks to human health (**Table 1**). Depending on the availability of contamination data at the time of calculation, different contamination databases were used for these simulations. Nevertheless, the calculations indicate an overall median acrylamide intake around 0.5 µg.kg $bw^{-1}.day^{-1}$. The Joint FAO/WHO Expert Committee on Food Additives (JECFA) estimated the average dietary acrylamide intake in the general population between 0.3 and 2.0 µg.kg $bw^{-1}.day^{-1}$, with intakes up to 5.1 µg.kg $bw^{-1}.day^{-1}$ for the 99^{th} percentile consumers (FAO/WHO 2005). The major contributing foods to the exposure were French fries, potato crisps, coffee, biscuits and bread. Other food items contributed less than 10% of the total exposure (Krokida *et al.* 2001; Konings *et al.* 2003; Svensson *et al.* 2003; Boon *et al.* 2005; Dybing *et al.* 2005; FAO/WHO 2005; Wilson *et al.* 2006; Mestdagh *et al.* 2007).

As shown in **Table 1**, children and adolescents tend to be more exposed to acrylamide, about 2 to 3 times more compared to adults (FAO/WHO 2002). This may be due to a combination of children's higher caloric demand relative to their body weight as well as their different dietary pattern, with higher consumption of certain foodstuffs rich in acrylamide, such as French fries and potato crisps (Dybing *et al.* 2005; Wilson *et al.* 2006). It is thus clear that certain subgroups demonstrate especially high exposure to acrylamide.

In order to evaluate the risk associated with abovementioned acrylamide intakes, the margin of exposure (MOE) approach was put forward recently (FAO/WHO 2005; EFSA 2005; Barlow *et al.* 2006). The MOE is defined as the ratio between a dose leading to tumours in experimental animals and the human intake. A smaller MOE thus represents a higher risk than a larger one. This safety margin can be used by risk managers for priority setting. For acrylamide, the MOE was calculated between 75 and 300 (FAO/WHO 2005; O'Brien *et al.* 2006). In comparison, the margin of benzo(*a*)pyrene, a polyaromatic hydrocarbon and well known carcinogen formed in charbroiled food, was determined between 10000 and 25000. This clearly indicates the human health concern of acrylamide.

Although many epidemiological studies could not prove convincing links between human tumorigenesis and acrylamide intake (Parzefall 2008) – probably because of the limited statistical power – a positive association was found recently between dietary acrylamide intake and renal cell cancer risk (Hogervorst *et al.* 2008). Appropriate efforts in the entire production process to reduce acrylamide levels in foodstuffs should thus continue. A first and important step to realize this goal is to elucidate the different pathways of acrylamide formation, as described in the following section.

Table 1 Results of acrylamide exposure estimations (µg.kg $bw^{-1}.day^{-1}$) in different countries.

Country	**Reference**	**Population group**	**Exposure (µg.kg $bw^{-1}.day^{-1}$)**		
			Mean	**P 50**	**P 95/P 90***
Belgium	Matthys *et al.* 2005	adolescents (13 – 18 y)		0.5	1.1
Belgium	Mestdagh *et al.* 2007	convenience sample (18 – 35 y)	0.5	0.4	1.5
The Netherlands	Boon *et al.* 2005	total population (1 – 97 y)		0.5	1.2
		young children (1 – 6 y)		1.1	2.0
The Netherlands	Konings *et al.* 2003	total population (1 – 97 y)	0.5	0.2	0.6
		children - adolescents (7 – 18 y)	0.7	0.2	0.9
		young children (1 – 6 y)	1.0	0.3	1.1
Germany	Madle *et al.* 2003	total population	0.6		
	Mosbach-Schulz *et al.* 2003	young children (4 – 6 y)	1.2		
France	AFFSA 2003	adults (> 15 y)	0.5		1.1
		children (3 – 14 y)	1.4		2.9
Norway	Dybing and Sanner 2003	males (16 – 79 y)	0.5	0.4	1.2*
		females (16 – 79 y)	0.5	0.4	1.0*
Sweden	Svensson *et al.* 2003	adults (18 – 74 y)	0.4	0.4	0.9
US	DiNovi 2006	total population (> 2 y)	0.4		1.0*
		young children (2 – 5 y)	1.1		2.3*

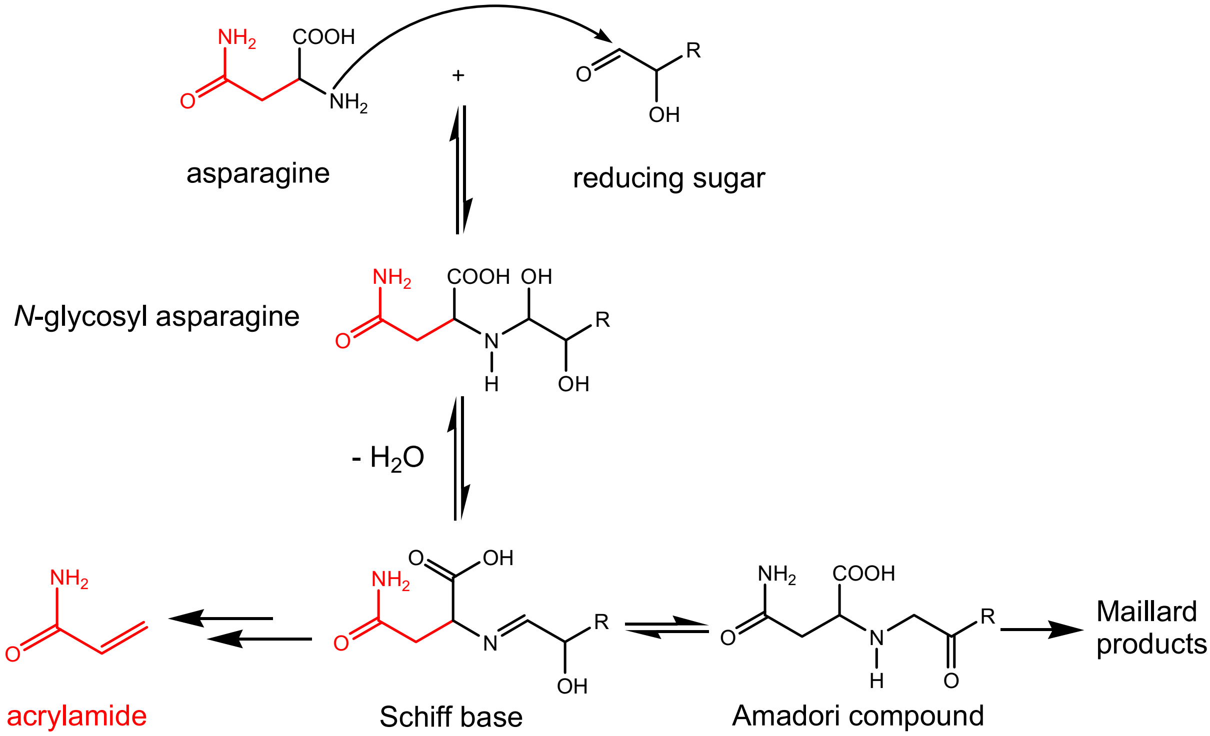

Fig. 3 Simplified overview of acrylamide formation as a side reaction of the Maillard reaction. Based on Mottram *et al.* (2002) and Stadler *et al.* (2002).

PATHWAYS OF ACRYLAMIDE FORMATION

In general, raw or boiled foodstuffs do not contain acrylamide, indicating that a dry heating process (e.g. frying or toasting) is required to form acrylamide. Pyrolysis experiments of model systems composed of amino acids and sugars demonstrated that acrylamide is indeed formed during the Maillard reaction, the non-enzymatic browning reaction responsible for the typical and desirable colour and taste of e.g. baked bread or fried potatoes. Free asparagine turned out to be the crucial participant in the production of acrylamide. Upon pyrolysis, asparagine alone may release acrylamide by thermally initiated decarboxylation and deamination. Yet, this yield increased a few hundredfold in the presence of (reducing) sugars. These findings were confirmed by the fact that acrylamide is formed in heated potato and cereal products, which contain reducing sugars and are particularly rich in free asparagine (Mottram *et al.* 2002; Stadler *et al.* 2002; Weisshaar and Gutsche 2002).

By means of mass spectral studies, using ^{15}N-labelled asparagine and ^{13}C-labelled glucose, it was unambiguously demonstrated that the amide nitrogen and the three-carbon backbone of acrylamide originated both from the corresponding positions in the asparagine molecule, as shown schematically in **Fig. 3** (Mottram *et al.* 2002; Stadler *et al.* 2002; Weisshaar and Gutsche 2002). The sugar backbone and α-amino group of asparagine was thus not incorporated in the acrylamide molecule. The (desired) Maillard reaction and (undesired) acrylamide formation thus share similar precursors. Consequently, the challenge of food scientists consisted out of lowering the formation of acrylamide, while safeguarding product quality and palatability, caused by Maillard reaction products.

Other precursors have also been proposed, such as 3-aminopropionamide (3-APA) (Granvogl *et al.* 2004; Schieberle *et al.* 2005). Although this component was detected as a transient intermediate of acrylamide during thermal degradation of free asparagine in the presence of a reducing sugar, 3-APA was also found in raw potatoes in different amounts (Granvogl *et al.* 2004; Bagdonaite *et al.* 2006). Moreover, 3-APA can be generated in an enzyme-catalysed reaction directly through decarboxylation of asparagine. This 'cold' biochemical pathway to 3-APA, i.e. bypassing the Maillard reaction and obviating the need of reducing sugars, may thus also contribute to the final amount of acrylamide in potato products. Recent studies however indicate that this biochemical formation route is probably marginal in comparison to the Maillard pathway (Bagdonaite *et al.* 2006).

AGRONOMICAL FACTORS AFFECTING THE FORMATION OF ACRYLAMIDE IN POTATOES

Research concerning fried potato products has indicated that the raw material quality and composition is of crucial importance in the mitigation of acrylamide. The strong susceptibility to acrylamide formation of potatoes is ascribed to the abundance of free asparagine, which is present in considerable excess compared to the amount of reducing sugars in the tuber. Consequently, the reducing sugar content can be considered as the limiting factor for acrylamide formation. Several studies could demonstrate a good linear

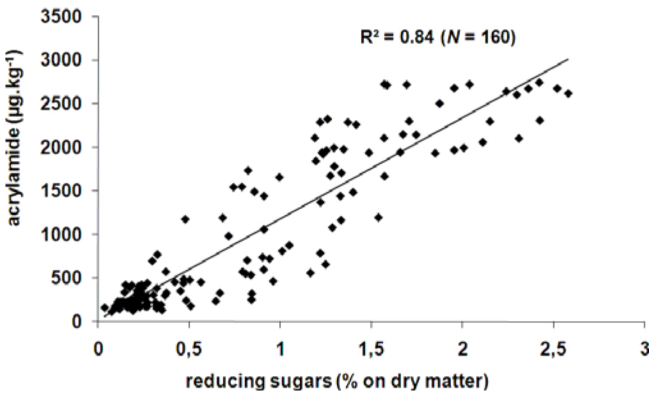

Fig. 4 Acrylamide formation as a function of the reducing sugar content in the potato tuber [3 min par-frying and 2 min finish frying, both at 180°C]. Reprinted from **De Wilde T, De Meulenaer B, Mestdagh F, Govaert Y, Vandeburie S, Ooghe W, Fraselle S, Demeulemeester K, Van Peteghem C, Calus A, Degroodt JM, Verhé R** (2005) Influence of storage practices on acrylamide formation during potato frying. *Journal of Agricultural and Food Chemistry* **53**, 6550-6557 with kind permission from the American Chemical Society (©2005).

correlation between acrylamide formation and reducing sugar content, as illustrated in **Fig. 4**. Yet, sucrose and free asparagine content did not correlate (Amrein *et al.* 2003; Chuda *et al.* 2003; Haase *et al.* 2003; Amrein *et al.* 2004; Becalski *et al.* 2004; De Wilde *et al.* 2005; De Wilde *et al.* 2006a; Gökmen *et al.* 2006; Brunton *et al.* 2007). Other studies however showed that the competition between asparagine and amino acids, different from asparagine and thus not generating acrylamide, may also be a determinant of the amount of acrylamide formed (Elmore *et al.* 2007).

Potato cultivar

Different potato cultivars may have a different chemical composition. Some varieties, such as Tebina and Quincy, are considered to be unsuitable for frying purposes, because of too high reducing sugar contents. Cultivars used for the production of potato crisps, such as Saturna and Lady Claire, are bred and selected for low sugar content and are therefore less susceptible to acrylamide formation upon frying (Amrein *et al.* 2003; Amrein *et al.* 2004; Olsson *et al.* 2004; De Wilde *et al.* 2006a). However, it is obvious that also other agronomical factors, besides the factor cultivar, have a considerable, if not more important impact on the reducing sugar content of the tuber, as discussed below.

Fertilization and soil

Since the potato is a crop with high nutrient requirements, heavy fertilization is routinely applied (Mondy and Koch 1978). Due to environmentally related problems in various countries, there is however a growing legal pressure to decrease the amount of nitrogen fertilization applied in general agriculture. It was observed that the free asparagine content increases with increasing nitrogen fertilization (De Wilde *et al.* 2006b). This can be explained by the fact that the accumulation of free asparagine may be a mechanism by which the potato tuber copes with excess of nitrogen fertilizer (Eppendorfer and Bille 1996). The higher uptake of nitrogen also leads to a reduction in available mono- and disaccharides, because these are used for the biosynthesis of amino acids (Kolbe 1990). Decreasing nitrogen fertilization consequently leads to increased reducing sugar contents and subsequent acrylamide formation. Yet, the extent of sugar increase appears to be cultivar dependent. Another study reported that a moderate nitrogen fertilization in combination with a good provision of potassium resulted in low contents of free asparagine and reducing sugars (Heuser *et al.* 2005). On the other hand, increasing phosphorus nutrition gave rise to increased reducing sugar contents at harvest (Kolbe *et al.* 1995). Sulfur deprivation led to a decrease in acrylamide formation (Elmore *et al.* 2007). Based on these studies, it seems thus important to find an appropriate balance between the level of fertilizers in order to obtain a tuber, low in potential to generate acrylamide, but on the other hand to consider the environmental impact and legal fertilization limits (De Wilde *et al.* 2006b).

The type of soil does however not seem to have a significant impact on the acrylamide formation during frying (De Wilde *et al.* 2006a).

Climatological conditions and harvest

Apart from differences in fertilization level and cultivar, potato growers and the potato processing industry are confronted with a year-to-year variation in the raw material characteristics. Due to the variability in the climatological conditions, a significant change in the reducing sugar and free asparagine content could be observed. Exceptional warm and dry summers gave rise to lower reducing sugar contents (on dry matter basis) and thus a lower susceptibility for acrylamide generation during subsequent frying (Davies *et al.* 1989; De Meulenaer *et al.* 2008). Exceptional rainfall in the final stages of the growth season gave rise to a lower dry matter content and increase in the nitrogen fraction (on dry matter basis), probably due to an extra uptake of available nitrogen fertilizer (De Meulenaer *et al.* 2008). Apart from changes in the reducing sugar content, other compositional parameters, such as the 3-aminopropionamide content (Granvogl *et al.* 2004), could also exert an influence on the complex mechanism of acrylamide generation, as indicated earlier.

The harvest time, linked with the maturity of the tuber, is often dependent upon the climatological conditions (Hertog *et al.* 1997a, 1997b). During maturation, nutrients are transported from the leaves to the tuber. The reducing sugar content in immature and thus smaller potatoes is higher since the degree of translocation of sugars from leaves to tuber still exceeds the degree of transformation of sugars to starch (Nelson and Sowokinos 1983; Misra and Chand 1990; Ohara-Takada *et al.* 2005). Consequently, smaller (less mature) tubers have a higher potential to form acrylamide upon frying (De Wilde *et al.* 2006a). It is moreover known that the state of maturity at the time of harvest determines the storage behaviour, through the initial amount of enzymes or enzyme systems, responsible for sweetening, as discussed below (Hertog *et al.* 1997a, 1997b).

Potato storage

After harvest (around the end of September), potatoes are usually stored at 8°C for a period of several months. This storage temperature does not significantly influence the reducing sugar content and the acrylamide formation upon subsequent frying (Noti *et al.* 2003; Olsson *et al.* 2004; De Wilde *et al.* 2005, 2006a) (**Fig. 5**). Some cultivars are however more susceptible to senescent sweetening upon long-term storage, involving an increase in sugar content inside the tuber. This enzymatic process also depends upon climatological conditions prior to harvest, occurs more rapidly at higher storage temperatures (> 8°C) and is related to the start of sprout growth (Burton 1989a; Amrein *et al.* 2004). To avoid sprouting, chemical sprout suppressing agents may be used, although the use is not always permitted and desired by the consumer. Also low-dose irradiation can be applied. The use of sprout inhibitors does not result in a significant influence on the composition of the tuber and the potential of acrylamide formation during subsequent frying operation (Noti *et al.* 2003; De Wilde *et al.* 2005; Gökmen *et al.* 2006).

Due to climatological conditions, especially during a cold winter period in Northern countries, lower storage temperatures may however be unavoidable. These colder pre-

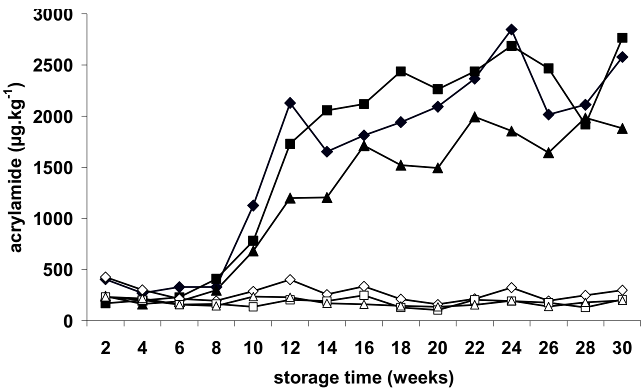

Fig. 5 Influence of storage time and temperature on acrylamide formation during frying of three potato varieties (Bintje, Ramos, Saturna) stored at 4°C and 8°C over 30 weeks. (♦ = Bintje, 4°C; ■ = Ramos, 4°C; ▲ = Saturna, 4°C; ◊ = Bintje, 8°C; □ = Ramos, 8°C; Δ = Saturna, 8°C). Reprinted from **De Wilde T, De Meulenaer B, Mestdagh F, Govaert Y, Vandeburie S, Ooghe W, Fraselle S, Demeulemeester K, Van Peteghem C, Calus A, Degroodt JM, Verhé R** (2005) Influence of storage practices on acrylamide formation during potato frying. *Journal of Agricultural and Food Chemistry* **53**, 6550-6557 with kind permission from the American Chemical Society (©2005).

servation conditions make potato tubers less susceptible to diseases (Burton and Wilson 1978; Blenkinsop *et al.* 2002). Since sprouting can moreover be inhibited without the use of chemicals, this preservation technique is suitable for organic potato production (De Wilde *et al.* 2005). Presumably to protect themselves against frost, potatoes however start to mobilize sugars from the starch inside the tuber at temperatures below 8°C (Coffin *et al.* 1987; Burton 1989b; Davies *et al.* 1989; Peshin 2000; Sowokinos 2001; Blenkinsop *et al.* 2002). This physiological reaction, also known as low temperature sweetening, makes the tubers more prone to undesired Maillard browning and dramatically increases the acrylamide formation upon subsequent frying (Biedermann *et al.* 2002; Noti *et al.* 2003; Olsson *et al.* 2004; De Wilde *et al.* 2005; Ohara-Takada *et al.* 2005; Matsuura-Endo *et al.* 2006; Burch *et al.* 2008; Viklund *et al.* 2008). From **Fig. 5**, it can moreover be observed that this susceptibility to low temperature sweetening is cultivar dependent. As indicated in previous section, the state of tuber maturity at the time of harvest also determines the storage behaviour, through the initial amount of enzyme responsible for sweetening (Hertog *et al.* 1997a, 1997b).

Unlike senescent sweetening, low temperature sweetening is at least partially reversible (Burton 1989b). It is thus possible to achieve a significant reduction in the reducing sugar content after reconditioning of the cold-stored tubers for a period of 3 weeks at 15°C. These higher temperatures provoke an increased respiration rate inside the tuber. As a result, the reducing sugar content decreases through respiration and part of the sugars are again converted into starch. This operation step largely reduces the risk of later acrylamide formation, although this decrease in sugar content is not completely reversible and different rates of reduction were observed between potato cultivars (Peshin 2000; Biedermann *et al.* 2002; Blenkinsop *et al.* 2002; De Wilde *et al.* 2005).

Besides storage temperature, light also seems to activate potatoes, initiating the formation of reducing sugars and subsequent acrylamide formation upon frying (Biedermann *et al.* 2002). In addition, there is an increased synthesis of glycoalkaloids (such as solanidine), with known toxic properties, at the periphery of the tuber (Burton 1989b). So, potatoes should be stored at temperatures of about 8-10°C in the dark. In addition, the gaseous composition of storage atmosphere has also been shown to affect the sugar content of potatoes. Depending on other agricultural factors, low oxygen levels (in an atmosphere of nitrogen gas) suppressed sugar accumulation upon low-temperature storage, while increased carbon dioxide concentrations led to a rise in sugar content (Kumar *et al.* 2004). On large industrial scale, the control of these atmosphere conditions seems economically however less feasible.

To conclude, it can be stated that the raw material composition is of crucial importance to reduce acrylamide formation during frying of potato products. This concerns mainly the reducing sugar content and to a lower extent the asparagine content. The potato variety should be well chosen, the cultivation and storage conditions should be well managed to obtain tubers with a minimum amount of sugars. Potatoes used for roasting or frying should contain less than 1 $g.kg^{-1}$ fresh weight of reducing sugars (Biedermann-Brem *et al.* 2003; De Wilde *et al.* 2005). However, adverse and moreover uncontrollable climatological circumstances make it sometimes difficult, if not impossible, to fulfil these requirements (De Meulenaer *et al.* 2008). Specific plant-breeding programmes could be set up, selecting specific cultivars which are more resistant to unfavourable climatological conditions before and after harvest (Halford *et al.* 2007). Since this is a lengthy process, genetic modification of plant materials could be an alternative, for example by inhibiting the enzymatic activity to reduce the formation of reducing sugars in the tuber (Friedman 2003) or by lowering the free asparagine content. Recently, a genetically modified potato variety was produced in the US, by reducing the expression of specific genes, responsible for low-temperature sweetening (Rommens *et al.* 2006). Due to legal considerations and public acceptability it is however currently not evident to use genetically engineered products within the European Union (EFSA 2003).

Since some agronomical factors remain difficult or not controllable, several parameters later in the production process must be optimized to (further) decrease the potential of acrylamide formation during frying. Below, several process-bound factors are discussed in order to identify their importance to mitigate the final acrylamide content. Additionally, these measures must be placed in the perspective of consumer acceptance, since it is known that any modification performed on the raw material composition or during processing may influence the Maillard reaction and its products, and concomitantly the organoleptic properties of the food.

EFFECT OF POTATO PROCESSING PARAMETERS ON ACRYLAMIDE FORMATION

Initial processing steps

The potatoes entering the processing factory are first graded according to size (**Fig. 2**). As indicated above, smaller tubers tend to form more acrylamide upon frying (De Wilde *et al.* 2006a). Subsequently, they are peeled, washed and cut. The potato cuts are again calibrated by size. Potato strips are thereupon blanched, as discussed below. Potato slices (for the production of crisps) are merely soaked in hot water. Due to the high surface-to-volume ratio of this product, soaking smoothly removes (reducing) sugars and superficial starch and reduces the formation of acrylamide during frying (Haase *et al*. 2003). Obviously, soaking extracts less precursors from the potato cuts compared to blanching due to the lower temperatures applied (Kita *et al*. 2004).

Blanching process

In the production process of French fries, the potato strips are carried through a hot water bath with steam injection. This so-called blanching treatment gives the fries a more uniform colour after frying, inactivates enzymes and forms a layer of gelatinized starch that limits oil absorption and improves texture. It also extracts reducing sugars from the potato strips, leading to less acrylamide (Kita *et al.* 2004; Pedreschi *et al.* 2007b; Burch *et al.* 2008; Mestdagh *et al.* 2008d). As shown in **Fig. 6**, the blanching temperature had a more significant impact on the acrylamide content compared to the blanching time. Lower blanching temperatures would thus require much longer blanching times in order to obtain similar acrylamide reductions.

Extreme blanching conditions might, however, cause a significant loss in nutrients, product taste, colour and texture (Arroqui *et al.* 2002; Carbonell *et al.* 2006). It was for example demonstrated that (conventional) blanching at high temperature for a short period of time (97°C, 2 min) may upon frying result in a higher oil content and inferior textural properties compared to unblanched strips (Alvarez *et al.* 2000). Blanching at somewhat lower temperatures (55-70°C) for a period between 15 and 60 min did, however, show to improve the textural quality of French fries and lowered the oil uptake upon frying, as compared to unblanched potato strips (Aguilar *et al.* 1997). These milder temperatures would rather activate the pectin methyl esterase (PME). This enzyme produces free carboxylic groups which can react with naturally present divalent ions, creating a more rigid structure and increasing firmness (Canet *et al.* 2005). Taking these product quality aspects and **Fig. 6** into account, a blanching step at temperatures of about 70°C for about 10-15 min should be considered in the industrial production process, depending on the amount of reducing sugars in the raw material. This was shown to reduce the acrylamide content with about 65% and 96% for French fries and potato crisps, respectively (Mestdagh *et al.* 2008d).

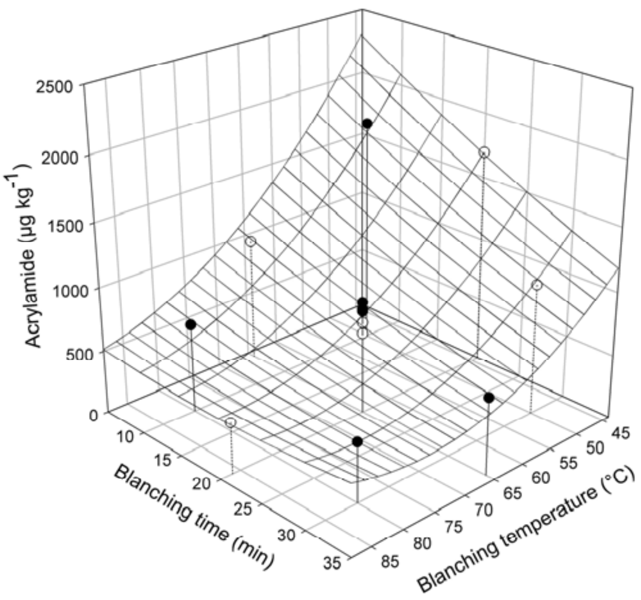

Fig. 6 Response surface plot of the acrylamide content in French fries as influenced by blanching time and temperature, with the measured values above (●) and below (o) the surface. Reprinted from **Mestdagh F, De Wilde T, Fraselle S, Govaert Y, Ooghe W, Degroodt JM, Verhé R, Van Peteghem C, De Meulenaer B** (2008d) Optimization of the blanching process to reduce acrylamide in fried potatoes. *LWT - Food Science and Technology* **41**, 1648-1654, with kind permission from Elsevier B. V. (©2008).

The abovementioned experiments (**Fig. 6**) were performed in tap water, with a low potato/water ratio, but this is not the case in an industrial production process. Generally considered, the water in an industrial blancher is completely drained and filled with fresh water only weekly, or is during production partially refreshed by means of a continuous input of fresh water in the blancher, coupled with an overflow mechanism to remove the water, loaded with solubles. In both cases the water is loaded with soluble components extracted from the potato cuts and the concentration of these components reaches a steady-state level in the blanching water. It was shown that the extraction efficiency of reducing sugars was over 10% lower when the potato cuts were blanched in this “process water”, leading to over 10% less reduction in the final acrylamide content. An adequate refreshment of the blanching water thus increased the extraction efficiency (Mestdagh *et al.* 2008d). Since continuous replacement of blanching water with fresh water is economically and ecologically not feasible, new blanching procedures could be developed, during which the rate-limiting acrylamide precursors are selectively metabolised (e.g. by enzymes).

Additives

In order to further lower the potential of acrylamide formation, food-grade additives can be dissolved into the blanching (or soaking) water. In the industrial French fry production, pyrophosphate is already used to diminish darkening of the blanched potato cuts. As shown in **Table 2**, it also significantly reduces acrylamide, at a concentration level of 50 mM (Mestdagh *et al.* 2008e). The currently applied concentration of pyrophosphate in industry is however only about 2.5 mM, probably leading to less pronounced acrylamide reductions. Furthermore, organic acids such as acetic, lactic or citric acid can efficiently lower the pH and accordingly the amount of acrylamide (**Table 2**). The mitigating effect at low pH was attributed to protonation of asparagine amino groups which would block the nucleophilic addition of asparagine with a carbonyl compound (e.g. reducing sugar). Several salts such as Na^+, Ca^{2+} or Mg^{2+} or amino acids different from asparagine are indicated as efficient acrylamide reducing agents (Rydberg *et al.* 2003; Gökmen and Senyuva 2007; Pedreschi *et al.* 2007a, 2007b; Mestdagh *et al.* 2008e; Ou *et al.* 2008). Furthermore, antioxidants were proposed as efficient acrylamide reducing agents (Becalski *et al*. 2003; Fernández *et al*. 2003; Zhang *et al*. 2007; Napolitano *et al*. 2008). Yet, it is not always clear whether the reduction was due to other parameters, changing simultaneously upon addition of the antioxidant extract, such as pH or amino acids present in the extracts. In other studies, no obvious correlation was observed between formation of acrylamide and antioxidants (Rydberg *et al.* 2003; Ehling and Shibamoto 2005).

In addition, some of the abovementioned agents were shown to reduce the absorption of oil during the frying process (**Table 2**) by changing textural characteristics such as the product surface roughness and crust porosity (Mestdagh *et al.* 2008c). Besides influencing texture, these treatments may also alter other sensorial product characteristics (Low *et al.* 2006; Mestdagh *et al.* 2008c; Ou *et al.* 2008). An overdose of acid or $CaCl_2$ can respectively cause a sour or bitter aftertaste, or a too pale end product, making it unacceptable for the consumer. To avoid this, a controlled (computerized) dosage of the additives is required (Mestdagh *et al.* 2008c; Ou *et al.* 2008). Moreover, the agents must be compatible with additives already used in the production line, such as pyrophosphate. Addition of salts to blanching or soaking water might also increase oil degradation in the subsequent deep-frying step or can give rise to metal corrosion of the equipment. These and other practical considerations make the implication of additives in the production process of e.g. French fries a challenge. To deal with these issues, scaling-up experiments on (semi)industrial level are needed.

Fermentation and enzymatic treatment

Recently, lactic acid fermentation by *Lactobacillus plantarum* was proposed to effectively lower acrylamide formation upon subsequent frying (Baardseth *et al.* 2006). Accordingly, acrylamide precursors, such as reducing sugars, were metabolised, while the produced lactic acid lowered the product pH. Yet, incubation times up to 2h were proposed. The use of the enzyme asparaginase proved to effectively reduce the asparagine content of the raw material, reducing acrylamide formation upon subsequent frying

Table 2 Impact of several blanching agents on the pH of blanched potato slices, on the oil content and on the acrylamide reduction, in terms of percentage compared to water-blanched crisps (Mestdagh *et al.* 2008c).

	Concentration (mol/L)	Added component	pH slices	Oil content (%)	Acrylamide reduction (%)
		water (control)	6.7	40	0
acids	0.05	pyrophosphate	6.0	29	83
	0.025	citric acid	4.1	25	98
	0.025	acetic acid	4.8	29	80
	0.025	L-lactic acid	4.8	29	89
amino acids	0.05	glycine	6.6	35	58
	0.05	L-lysine	6.6	38	73
salts	0.1	NaCl	6.7	27	43
	0.05	$CaCl_2$	6.1	24	64
	0.03	$CaCl_2$ + Ca-lactate	6.3	23	50

(Pedreschi *et al.* 2008). A recent patent application (Soe *et al*. 2005) suggested the incubation of potato cuts in solutions containing the enzymes glucose isomerase and glucose oxidase, respectively, to selectively remove the rate-limiting acrylamide precursors and enable a closed-loop circuit of warm blanching water. This could save energy and water and reduce the environmental impact. In addition, it could increase the retention of other valuable components in the tuber such as amino acids and ascorbic acid, safeguarding the sensorial and nutritional product quality. The feasibility of such fermentation treatments within a high-speed production line, remains, however, to be proven. In addition, enzyme denaturation in the hot process (blanching) water could inactivate most of the enzyme present. As a consequence, extra (temperature-controlled) incubation reservoirs would have to be installed, increasing production costs, not counting the cost of the enzymes.

Drying

To reduce fat absorption and oil hydrolysis during frying, the surface of the blanched or soaked potato cuts is dried prior to frying (Mehta and Swinburn 2001; Choe and Min 2007). Drying between the pre-frying and finish frying step proved to decrease acrylamide formation during the latter stage, since shorter finish frying times were needed to obtain the same final product quality (Franke *et al*. 2005). Also drying of potato crisps after a shorter frying stage appeared to reduce the amount of acrylamide formed (Kita *et al*. 2005). This postdrying method also resulted in low-moisture potato crisps of good sensory quality, but was more time-consuming compared to the traditional frying step.

Frying process

During the (one or two step) frying operation, the potato cuts are immersed in an edible oil or fat heated above the boiling point of water. This process may therefore be considered a dehydration process. These conditions lead to high heat transfer rates, rapid cooking, browning, texture and flavour development, caused by the Maillard reaction (Farkas *et al*. 1996). Generally, acrylamide is formed at temperatures above 120°C and its generation is accelerated as the frying temperature increases. The acrylamide content increases exponentially towards the end of the frying process, as the surface temperature of the fried product approaches the deep-frying oil temperature. Consequently, a more intensive frying operation produces more acrylamide. Therefore, it was suggested to limit the frying temperature to 170-175°C. A decrease in oil temperature towards the end of the frying operation would be the ideal measure to decelerate the formation of acrylamide at the end of the frying process. For this, it was suggested to implement new technical specifications for fryers, enabling a controlled oil temperature profile during frying (Grob 2007). Yet, changing only the deep fryer specifications might not be very effective to mitigate acrylamide formation since many other parameters have a major impact on the oil temperature during the frying process, such as the initial temperature of the potato cuts and the oil/product ratio.

Frying under vacuum was proposed as an alternative (Granda and Moreira 2005). Since lower frying temperatures can be applied to obtain a product with desirable colour and final dry matter content, the acrylamide contents in the final product are much lower. Again, investments into new frying equipment are necessary for this.

The role of the deep-frying oil was investigated on several occasions. It was believed that the type of oil could affect acrylamide formation, due to the differing ability to transfer heat into foods (Gertz and Klostermann 2002; Becalski *et al.* 2003; Gertz 2004; Matthäus *et al.* 2004). Furthermore, oil degradation products, such as acrylic acid or acrolein, were also put forward as potential acrylamide precursors (next to reducing sugars and asparagine). However, contradictory results were obtained in different studies, suggesting that the impact of the deep-frying medium on acrylamide formation seems negligible (Mestdagh *et al.* 2008a).

Link between product colour and acrylamide

In many cases, there was a good correlation between the acrylamide content of fried potatoes and their colour (Jackson and Al-Taher 2005; Pedreschi *et al.* 2005, 2006, 2007b; Viklund *et al.* 2007). Generally, a darker-coloured product contains more acrylamide. However, this correlation was less close for large surface-to-volume material, such as potato crisps, in comparison with small surface-to-volume material, such as French fries. Data for potato crisps could thus not be extrapolated for French fries and vice versa (Taubert *et al.* 2004). Infusion of potato slices with different glucose and asparagine levels also broke the correlation. While both components increased the acrylamide formation, only glucose caused a significantly different product colour (Granda *et al.* 2005). It was furthermore shown that addition of fructose to potato cuts stimulated acrylamide formation to a higher extent than Maillard browning. The opposite effect was established for glucose (Mestdagh *et al.* 2008b). To improve Maillard browning, the potato processing industry applies in particular circumstances sugar soaking of blanched potato strips. This soaking treatment should thus preferentially be performed with glucose, rather than with fructose.

The fact that darker-coloured fries generally contain more acrylamide however allows the removal of pre-fried French fries with a darker colour from the production line using optical inspection techniques. In such a way, fries with a high potential to form acrylamide during the final frying stage cannot reach the consumer. In this respect, the entrance control upon delivery of potatoes at the processing plant should also be used as a valuable measure to reduce acrylamide in the final product. Generally, upon reception of potatoes, a standardised baking trial is performed in order to evaluate the colour of the fried potatoes. Batches generating a too dark colour during this entrance control can accordingly be rejected for frying, but can e.g. be used to produce potato flakes. In another way, the production line can be adjusted to lower the potential of acrylamide formation (e.g. by adjusting the blanching or soaking treatment). These measures are already ongoing in the potato industry, but are, till now, more focussed on final product quality (colour) rather than on acrylamide formation. Therefore, additional research is necessary to make this link between product colour at entrance control and acrylamide formation at the final end of processing.

CATERING AND CONSUMER

As discussed in the previous paragraphs, not only the agronomical and food processing sector, but also the consumer, have a big responsibility to lower the overall acrylamide exposure and to prepare qualitative and safe food. A thorough rinsing (blanching) in warm water prior to frying extracts acrylamide precursors form the surface of the potato cuts and lowers acrylamide formation upon subsequent frying. Moreover, it contributes to a more homogeneous colour of the final product. The frying temperature should not exceed 170-175°C and excessive browning should be avoided. The ideal final colour is considered to be gold-yellow, and certainly not brownish. The consumer is generally advised to follow a diverse dietary pattern composed of foods from many sources, low in fried foodstuffs, but rich in fruits and vegetables (Mestdagh *et al.* 2007).

Of course, the catering industry also plays a major role. Due to a considerable raise in out of home eating the last decennia, the role of caterers has further increased (Guthrie *et al.* 2002). Even if the agronomical and processing practices were optimal, large amounts of acrylamide can still be formed in the final product when not respecting the finish frying time and/or temperature. A recent study indicated that optimal preparation conditions of French fries, in combination with a nutritionally balanced menu, where the consumption of fruits and vegetables is encouraged, may significantly lower the acrylamide intake for its customers (Mestdagh *et al.* 2007).

CONCLUSIONS

To conclude, it can be stated that a farm-to-fork approach is indispensable to control acrylamide intake via the diet. Only with this integrated approach safer (fried) foodstuffs can be obtained, preserving the final product quality characteristics, which are of crucial importance for the consumer. From the data available in literature, it is clear that both the agronomical and industrial potato processors have put a lot of effort in finding ways to reduce the amount of acrylamide formed in their products. To communicate these findings to all stakeholders, an acrylamide "toolbox" was composed by and published on the European Confederation of the food and drink industries (CIAA) website and on the website of the DG Health and Consumer Protection (CIAA 2006). Further efforts are however still necessary to implement some reducing measures on large scale and to further inform the consumer and catering sector about the possibilities to lower the acrylamide intake.

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