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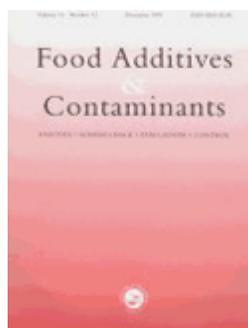
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Effective quality control of incoming potatoes as an acrylamide mitigation strategy for the French fries industry

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4 1 **Effective quality control of incoming potatoes as an acrylamide**
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7 2 **mitigation strategy for the French fries industry**
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17 **Abstract**

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4 18 The correlation between sugar levels in raw material (potatoes), brown colouring and formation of
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6 19 acrylamide in French fries was investigated. Such a study would allow the identification of incoming
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9 20 potatoes (raw material) with high potential for acrylamide-formation. Ten different potato varieties
10
11 21 commonly used in the Western European French fries industry were stored at 8°C and samples were
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13
14 22 taken throughout the storage time. The current quality control used in the French fries industry for
15
16 23 incoming potatoes is poorly correlated with acrylamide in the final product ($R = 0.74$). Changing the
17
18 24 quality control parameter from colour to reducing sugars in raw material did not improve the correlation
19
20
21 25 ($R = 0.72$). The best correlation was obtained with Agtron colour measurement after blanching and a
22
23 26 two stage frying ($R = -0.88$). From this study it could be concluded that alternative entrance control
24
25 27 measurements could provide a better mitigation of the acrylamide issue in French fries from the start of
26
27
28 28 the production. These alternatives however are less cost-effective and more difficult to implement.
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32 29 **KEYWORDS:** Acrylamide; Quality control; Colour; Reducing sugars; French fries
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30 Introduction

31 Fried potato products are very familiar and popular among many gastronomic cultures. French fries
32 (also known as chips or fries), either fresh or pre-frozen, are widely industrially produced and consumed
33 after a final deep fat frying step. During this process, acrylamide, a probable human carcinogen is
34 formed (IARC 1994). Exposure studies demonstrate that French fries represent a great source of dietary
35 acrylamide for consumers (Mestdagh et al. 2007).

36 This process contaminant is formed during the heating process at temperatures above 120°C (Tareke
37 et al. 2002) and is known to be linked to the Maillard browning reaction. The free amino acid asparagine
38 and the reducing sugars (fructose and glucose) have been identified as the main precursors for its
39 formation (Becalski et al. 2003; Mottram et al. 2002; Stadler et al. 2002). Since generally the amount of
40 free asparagine in potato tubers largely exceeds the amount of reducing sugars, it is the latter which
41 determines the degree of acrylamide formation and the Maillard browning upon frying (Amrein et al.
42 2003; De Wilde et al. 2005). Multiple factors have been demonstrated to influence the reducing sugar
43 content in potatoes, for example, potato cultivar (Biedermann et al. 2002; De Wilde et al. 2006), storage
44 time and temperature (Blenkinsop et al. 2002; De Wilde et al. 2005).

45 For the mitigation of acrylamide formation in French fries, several strategies may be considered, for
46 instance, the selection and storage of the raw material, adaptation of processing conditions, and pre-
47 treatments applied prior to par-frying (CIAA 2006; Foot et al. 2007). Predicting the sensitivity of
48 incoming potatoes for the formation of acrylamide would provide a quality control tool of great aid for
49 the French fry industry in their food safety management system. This would allow preventing the
50 problem at the start of the production process. The current quality control at the reception point of the
51 raw material potatoes is done based on colour evaluation with USDA/Munsell colour chart (after a short
52 frying test, typically 180°C for 3 min) (UEITP 2007). This quality control relates raw material to colour
53 specifications of final product (customers demand) and accordingly, either raw material is rejected for
54 processing or appropriate process adjustments are taken (e.g. blanching conditions).

1 55 The objective of this study was to identify parameters which best predict the sensitivity of potatoes at
2
3 56 the start of the production process for acrylamide formation during frying French fries. To our
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5 57 knowledge, an elaborate correlation study considering a combination of the three most obvious
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7 58 parameters (reducing sugars, colour and acrylamide) together in French fries has not yet been
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10 59 performed. Therefore, the correlation between reducing sugars in the raw material, the brown colouring
11
12 60 and the formation of acrylamide in this fried potato product was investigated. Furthermore, threshold
13
14 61 values (THV) were determined considering a hypothetical acrylamide limit of $500 \mu\text{g kg}^{-1}$ (based on the
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16
17 62 German system of signal values) for the most relevant parameters obtained from the correlation study.
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19 63 Additionally, samples were categorized based on the prediction obtained with the application of the
20
21 64 threshold values and evaluated according to acrylamide levels of the final product.
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24 65

26 66 **Materials and methods**

28 67 *Reagents and chemicals*

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31 68 All reagents and chemicals used for the acrylamide and sugar analysis were described in Mestdagh et
32
33 69 al. (2005) and De Wilde et al. (2005) respectively.
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36 70 *Raw material*

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38 71 Potato (*Solanum tuberosum* L.), varieties Bintje, Fontana and Asterix (Belgium); Russet Burbank,
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40 72 Lady Olympia and Markies (The Netherlands), Innovator and Victoria (France); Agria (Germany); and
41
42 73 Maris Piper (UK) were used for the study. One lot of each variety was supplied by a single producer to
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44 74 be studied throughout storage. Additionally, all lots were approved for frying according to the industry
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46 75 entrance control criteria (size above 50 mm and minimal under water weight of 380 g). All tubers were
47
48 76 harvested in 2007, treated with CIPC and stored at 8°C. Samples were taken on five different points in
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50 77 time (January-June).
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54
55 78 Fully refined palm oil (Cargill Refined Oils-Europe) was used for all the frying experiments.
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57 79 *Preparation of French fries*

80 Thirty five potato tubers from each variety were peeled and cut into strips (1 cm x 1 cm x 3 cm) with
81 a French fries-shaped cutter. To obtain strips with similar dimensions, parts that were in contact with the
82 outer peel of the tuber were rejected for frying. Subsequently, only the potato strips originating from the
83 central part of the potato were used for the experiment. These were washed with tap water for 1 min,
84 superficially dried on absorbent paper and divided into three groups (Figure 1). A first group, (Entrance
85 parameters) was fried at 180°C for 3 min. A second group (unblanched Final parameters) was par-fried
86 at 180°C for 90 s, frozen overnight and fried at 175°C for 150 s. The third group (blanched Final
87 parameters) included a blanching step (70°C, 20 min, ratio potato/water of 1:5 (w:w)) prior to the par-
88 frying step (as described for the unblanched). Frying and par-frying were conducted in a semi-
89 professional thermostated deep-fryer (Fritel 2505, Belgium), containing 5 L oil and equipped with a
90 stirring mechanism to ensure a homogeneous temperature in the oil bath and a digital thermometer
91 controlling the stability of the oil temperature upon frying ($\pm 1^\circ\text{C}$). Directly after frying, the French fries
92 were cooled on absorbent paper and the surface colour was measured. Finally, the fries were thoroughly
93 homogenized for subsequent acrylamide and dry matter content analysis. The repeatability of the French
94 fries preparation method was previously assessed with a RSD of 15% (Mestdagh et al. 2005).

Acrylamide analysis

96 Acrylamide was determined in homogenized potato sample by LC-MS/MS as described previously
97 (Mestdagh et al. 2005). After aqueous extraction, using [2,3,3-d₃]acrylamide as internal standard, the
98 acrylamide extract was further cleaned up by solid-phase extraction. The extract was analyzed using
99 LC-MS/MS with positive electrospray ionization.

Sugar analysis

101 Mono- and disaccharides in homogenized potato sample were assessed by GC-FID analysis as
102 described earlier (De Wilde et al. 2005). Briefly, after aqueous extraction, addition of an internal
103 standard (phenyl- β -D-glucopyranoside), clean-up and drying under nitrogen, the filtrate was derivatized
104 and injected in a GC equipped with a flame-ionization detector.

105 *Analysis of dry matter content*

106 The dry matter content was determined, based on an official AOAC method (1990). Briefly, 5 g of
107 homogenized potatoes were mixed with calcinated sea sand and placed in the oven at 105°C until a
108 constant weight was obtained.

109 *Colour evaluation techniques*

110 The colour of the French fries was measured using a Konica Minolta spectrophotometer CM-2500d
111 (Konica Minolta, Osaka, Japan), operating in the CIE L*a*b* colour space, as described previously
112 (Mestdagh et al. 2008a). Immediately after cooling down, the French fries were closely aligned in a
113 plastic Petri dish. The readings were carried out in five-fold placing the instrument measuring port (8
114 mm aperture) at both sides of the dish. In such a way, the reflectance of a representative part of the
115 surface was measured. To exclude variable cover surface conditions, the specular reflectance was
116 included in the colour measurement. Following measurement conditions were applied: UV 100%;
117 standard illuminant D65 and observer angle 10°. The instrument was calibrated with a white calibration
118 tile and black calibration box. Data acquisition was performed using the Spectramagic NX colour data
119 software, version 1.52 (Osaka, Japan).

120 The colour was also evaluated using an Agron process analyzer (model E15-FP, Nevada, USA), as
121 described previously (Mestdagh et al. 2008a). Agron values range from 0 (black) to 100 (white). The
122 measurement was repeated three times by shaking up the fries in between each measurement. The
123 apparatus was calibrated using a white tile (Agron value of 100), according to manufacturer's
124 instructions.

125 Finally the colour was also evaluated using an USDA/Munsell colour chart (VIVA, Den Haag, The
126 Netherlands) which represents the method for entrance control of raw material (potatoes) currently used
127 in French fries industry (UEITP 2007). USDA/Munsell has a seven scoring system. The system includes
128 000; 00 and 0 (three different degrees of very lightly coloured French fries) followed by scores 01; 02;
129 03 and 04 (yellow to very brown French fries). All 35 fries from each variety were scored by comparing

130 their colour visually with the USDA/Munsell colour chart and the average score calculated.

131 *Statistical analysis*

132 Pearson correlation analysis was performed using SPSS 15.0 (SPSS inc., Chicago, IL) to determine
133 linear relationships between different parameters studied and acrylamide.

135 **Results and discussion**

136 *Reducing sugar contents of potato tubers, colour and acrylamide formation in French fries of 10* 137 *different potato varieties*

138 The present study included 10 varieties of potato tubers from Western Europe, representing the most
139 frequently used in potato processing industry. Five sampling points were taken from January to June.
140 Thus a sufficient spreading of the reducing sugar content of the raw material throughout storage could
141 be obtained, although in practice, these varieties are not necessarily processed in the potato industry
142 from January to June. Some varieties (Bintje, Victoria, Fonatana and Maris Piper) presented higher
143 levels of reducing sugars on June's sampling point, while no specific trend was found throughout the
144 initial storage period (data not shown). The reducing sugar concentrations of Asterix, Agria and Markies
145 did not change significantly throughout the whole storage period. Due to spoilage, the varieties
146 Innovator, Russet Burbank and Lady Olympia were not considered for the last sampling point. For these
147 varieties the reducing sugar contents did not change either significantly from January to May.

148 Table 1 presents the average reducing sugar contents in raw material and acrylamide formation in
149 French fries for the different potato varieties throughout storage. In addition, the min and max values of
150 reducing sugar contents before blanching are represented in between brackets for each variety. These
151 values do not necessarily correspond to the first and last sampling point for each variety. Varieties
152 Asterix and Maris Piper presented the highest reducing sugar content in raw material (averages 0.34 –
153 0.36 g 100 g⁻¹ FW), followed by Bintje, Innovator, Russet Burbank and Agria (averages 0.12 – 0.21 g
154 100 g⁻¹ FW). The lowest reducing sugar contents were observed with Lady Olympia, Victoria, Fontana

1 155 and Markies (averages 0.03 – 0.06 g 100 g⁻¹ FW). For the varieties which presented a higher reducing
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3 156 sugar concentration in June's sampling point, the contribution of this last point would not have
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5 157 influenced the variety grouping just mentioned. Since there are many factors which account for reducing
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7 158 sugar content in potato tubers, this hinders the comparison of this parameter for every variety with those
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10 159 reported in literature. Considering a relative comparison, Feltran et al. (2004) and De Wilde et al. (2006)
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12 160 observed, similarly as in this study, higher concentrations of reducing sugars for the variety Asterix
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14 161 relatively to the variety Bintje. However, both these varieties presented in this study higher reducing
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17 162 sugar contents comparatively to De Wilde et al. (2006), in a storage experiment carried out from the
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19 163 2003 harvest. This difference illustrates the need for careful interpretation of data, with respect to
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21
22 164 possible seasonal variation or other factors influencing the level of acrylamide precursors in raw
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24 165 potatoes. Comparing the three varieties Bintje, Agria and Markies, results showed higher concentrations
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26 166 of reducing sugars for the variety Bintje compared to Agria and Markies presenting the lowest
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29 167 concentration of all three. This was also observed among others (Amrein et al. 2003).

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31 168 Blanching is an important unit operation used in French fry processing, since it influences final
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33 169 product specifications, such as colour, fat content and texture (Moreira et al. 1999). In addition, during
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36 170 this step acrylamide precursors are leached out resulting in the reduction of acrylamide content in the
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38 171 final product (Mestdagh et al. 2008b). In general, potato processors increase the intensity of blanching
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41 172 conditions towards the end of the potato season due to senescent sweetening occurrence. These
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43 173 conditions needed to be kept constant during the course of the correlation study. Therefore blanching
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45 174 conditions applied in this study (70°C for 20 min) result from a compromise of moderate blanching that
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48 175 would generally be applied in the beginning of the season and a stronger treatment which would be
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50 176 applied by the end of the season. These conditions allowed a removal of reducing sugars over 38%
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52 177 (Table 1). This resulted in lighter coloured French fries (data not shown) and lower levels of acrylamide
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55 178 (average 48-86% reduction) in the final product (Table 1). Percentages of reducing sugars removal were
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57 179 not directly proportional to percentages of acrylamide reduction. For example, even though the varieties
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1 180 Lady Olympia and Victoria presented the same percentage of reducing sugars removal (50% average)
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3 181 after blanching, the latest presented a higher acrylamide reduction (86% average) compared to Lady
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5 182 Olympia (53% average). This observation suggests the influence on acrylamide formation of other
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7 183 compositional parameters which vary between cultivars besides reducing sugars.

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10 184 The current quality control applied in industry at the reception of raw material potatoes (surface
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12 185 colour of fried unblanched potato strips evaluated with a USDA colour chart) was additionally
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14 186 compared to two other colour evaluation methods previously studied (Mestdagh et al. 2008a), the CIE
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16
17 187 L*a*b* colour parameters and a process-specific Agtron analyzer. The latest is typically used in the
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19 188 French fries industry for on-line final product quality control. Lighter coloured French fries resulted
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21
22 189 from the reducing sugars removal during blanching treatment. This has reflected in an increase of
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24 190 Agtron value and a decrease of USDA and a* values. L* and b* values did not vary significantly (data
25
26 191 not shown).

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29 192 *Correlation study between reducing sugar content of the raw material, colour and acrylamide*
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31 193 *formation in French fries*

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33 194 The correlation between sugar content in the raw material, colour and acrylamide formation in
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36 195 French fries was investigated. Figures 2-5 demonstrate that relationships between the different
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38 196 parameters evaluated in this study and acrylamide are best described as linear. Different trends were
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41 197 observed for colour parameters and acrylamide at entrance before and after blanching, Figures 2-4 (I).
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43 198 Such difference was less evident when relating final parameters with acrylamide as shown by Figures
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45 199 2-4 (II). Two factors may contribute for this variation. The influence of different frying conditions
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48 200 (one stage frying vs two stage frying and different frying temperatures) probably had an effect on
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50 201 acrylamide formation, and secondly the removal of other acrylamide precursors besides reducing
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52 202 sugars (e.g. 3-aminopropionamide) during the blanching step. On the other hand, no difference was
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55 203 observed between trends obtained with the parameter reducing sugars and acrylamide before and after
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57 204 blanching (Figure 5). Since blanching influenced the trends between the different parameters and
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1 205 acrylamide, combining the data (unblanched and blanched) for the correlation study would not be
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3 206 relevant. Moreover it should be realized that processed French fries are always blanched, so by
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5 207 keeping the data separated, the study is more representative towards the industrial practice. Therefore,
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7 208 Pearson correlation coefficients (R) presented in Table 2 were determined considering acrylamide
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10 209 results from blanched samples only. This represents the most realistic approach to find a predictor for
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12 210 acrylamide content in the final product.

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14 211 As mentioned in literature (Amrein et al. 2003; Becalski et al. 2004; De Wilde et al. 2005;
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16
17 212 Mestdagh et al. 2008a) for potato products, a correlation between reducing sugars and acrylamide
18
19 213 formation was found (Figure 5 and Table 2). Similarly, no link was established between sucrose and
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22 214 acrylamide (De Wilde et al. 2006). A better correlation was obtained between fructose and acrylamide
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24 215 compared to the reducing sugar glucose. Mestdagh et al. (2008), described an excess of fructose
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26 216 compared to glucose stimulated acrylamide formation to a higher extent than Maillard browning.

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29 217 As shown on Table 2, among L*a*b* parameters, the best correlation was found between a* and
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31 218 acrylamide. This was also observed by Mestdagh et al. (2008) although an exponential relationship
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33 219 between a* and acrylamide was obtained. In that study higher levels of sugars and consequently higher
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36 220 contents of acrylamide were formed, giving rise to a different relationship. Both a* and Agtron
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38 221 parameters presented a better correlation with acrylamide in the final product after blanching and a two
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40 222 stage frying (R = 0.80 and R = -0.88 respectively) compared to the short frying used for entrance control
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43 223 (R = 0.77 and R = -0.83 respectively). A different trend was observed with the USDA colour evaluation
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45 224 method. The current entrance control (short frying test 180°C, 3 min and USDA colour measurement),
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48 225 used for the prediction of other product specifications rather than acrylamide, is poorly correlated to
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50 226 acrylamide in the final product (R = 0.74). This method allows only a five grade classification scale.
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52 227 Moreover, such classification is rather subjective since it is done by comparing visually the colour of the
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55 228 product with the colour chart. Analyzing reducing sugars in raw material (based on fresh weight) does
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57 229 not improve the correlation with the acrylamide of the final product (R = 0.72). A better correlation is
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1 230 obtained with Agtron process analyzer after frying at 180°C for 3 min (R = -0.83). Agtron colour
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3 231 measurements after blanching (70°C, 20 min) and a two stage frying (180°C, 90 s and 175°C, 150 s)
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5 232 obtained the best correlation regarding acrylamide in final product (R = -0.88).
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7 233 Based on the raw material used and the process conditions (blanching and frying) applied in this
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10 234 study, colour evaluation with Agtron allowed a better correlation with acrylamide compared to the
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12 235 reducing sugar contents. For the practical implementation in the food industry, using a colour parameter
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14 236 as an acrylamide predictor in raw material is more practical than analyzing sugar contents. However,
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17 237 results indicate that the current quality control of raw material potatoes, can be improved towards
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19 238 acrylamide prediction by changing colour evaluation method from USDA colour chart to the Agtron
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22 239 process analyzer.
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24 240 The correlation study combined with a specific acrylamide level in French fries could provide an extra
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26 241 preventive tool in their food safety management system, based on threshold values (THV) of the
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29 242 evaluated parameters best related to acrylamide. Such approach applied as a quality control
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31 243 measurement for raw potatoes at the reception point could prevent the acrylamide problem during
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33 244 further production.
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36 245 37 38 246 *Evaluation of threshold values* 39

40 247 The correlation study discussed above revealed the parameter best correlated to acrylamide formation
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43 248 in French fries was obtained with Agtron measurements. Reducing sugars are also a relevant parameter
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45 249 since they are chemically known to be the limiting precursor for acrylamide formation in potatoes. On
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48 250 the other hand USDA is the current quality control tool used for the approval or rejection of incoming
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50 251 potatoes in French fry industry. Consequently, these relevant parameters were considered for the
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52 252 determination of THV presented in Table 3. The calculation of such values was based on the linear
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55 253 relationships obtained between the different parameters with the acrylamide formed in the final product
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57 254 and considering a hypothetical acrylamide limit of 500 µg kg⁻¹. Relationships between colour
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1 255 parameters and acrylamide are represented by the broken line on Figures 2-3 (I - entrance parameters
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3 256 and II - final parameters) and relationships between reducing sugars and acrylamide on Figure 6 (solid
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5 257 line - entrance parameter and broken line - final parameter). The hypothetical acrylamide limit was
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7 258 selected based on the most recent signal value ($530 \mu\text{g kg}^{-1}$) established for French fries /chips by the
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10 259 German minimization concept for acrylamide. The signal value is defined as the lowest level of the 10%
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12 260 of products of each commodity group that have the highest acrylamide content (Göbel and Kliemant
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14 261 2007). The denominations “acceptable” (acrylamide $<500 \mu\text{g kg}^{-1}$) and “rejectable” (acrylamide >500
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17 262 $\mu\text{g kg}^{-1}$) will be adopted throughout the discussion of the results. In practice, incoming potatoes that
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19 263 would be classified as “rejectable” (within a certain limitation) would not be necessarily rejected but
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22 264 rather subjected to a more rigorous blanching treatment. This would allow further sugar removal thus
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24 265 rendering the French fries less prone to acrylamide formation and suit final product specifications
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26 266 (acrylamide $<500 \mu\text{g kg}^{-1}$). The application of the THV to the samples analyzed in this study resulted in
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29 267 a preliminary analysis of sample categorization (Table 3). Samples which are categorized as
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31 268 “acceptable” and have acrylamide $>500 \mu\text{g kg}^{-1}$ (third column of Table 3) could represent a non-
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33 269 conformity. On the other hand, samples which are categorized as “rejectable” and present acrylamide
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36 270 levels $<500 \mu\text{g kg}^{-1}$ (fifth column on Table 3) would have been in conformity (in respect to the
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38 271 acrylamide limit). Both scenarios are undesirable, however the first scenario could compromise final
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41 272 consumer safety, and the second scenario represents unnecessary “extra-precautions for industry” (e.g.,
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43 273 extra blanching) which translates in unnecessary costs.

45 274 The highest percentage of rejected samples (33%) was obtained with the application of the USDA
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47
48 275 THV after a short frying test (USDA <2.1). Worth noticing is the fact that 50% of those rejected
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50 276 samples correspond to samples “unnecessarily rejected”. Similarly, the application of the Agron THV
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52 277 (>57) after the short frying test presented a high percentage of samples rejected with acrylamide <500
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55 278 $\mu\text{g kg}^{-1}$ (45%). This value was reduced to 17% with the application of the THV for reducing sugars in
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57 279 raw potatoes ($<0.25 \text{ g } 100 \text{ g}^{-1} \text{ FW}$), although it should be noted that the number of samples in this
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280 category was too small to draw final conclusions.

281 On the other hand, considering the application THV for the final parameters (after blanching and fried
282 in two stages) different trends were obtained. The application of a THV for USDA <1.6 remains a poor
283 tool for predicting acrylamide in the final product, meaning that 56% of rejected samples had
284 acrylamide levels <500 $\mu\text{g kg}^{-1}$. Applying a THV for reducing sugars <0.11 g 100 g⁻¹ FW in blanched
285 potatoes increased the percentage of rejected samples with acrylamide <500 $\mu\text{g kg}^{-1}$ from 17% to 25%.
286 In contrast, the application of a THV for Agtron >61.0 showed major improvements. This application
287 resulted in a reduction of “unnecessarily rejected” samples to only 22% leading to the highest
288 percentage of correctly categorized samples (93%). Although this investigation was done on a lab scale,
289 and in addition a sensory evaluation of the final product was not considered, the THV obtained for
290 Agtron in the final product fits within the range of limits of consumer acceptability. Generally
291 considered, the final product colour is too bright at Agtron values above 75 and too dark below 55
292 (Mestdagh et al. 2008a).

293 When selecting a quality control parameter for raw material potatoes at the reception for acrylamide
294 mitigation purposes, an important aspect to consider when evaluating the THV application is the final
295 consumer safety (percentage of accepted samples with acrylamide >500 $\mu\text{g kg}^{-1}$). These percentages
296 ranged from 3 to 12% for the parameters presented on Table 3. The lowest percentage (3%) was
297 obtained with the application of the THV for Agtron final (after blanching and fried in two stages). The
298 parameter USDA final (after blanching and fried in two stages) allowed the highest percentage of
299 accepted samples with acrylamide >500 $\mu\text{g kg}^{-1}$ (12%).

300 It should be kept into account that the THV for quality control tools mentioned in this paper are
301 directly related to the hypothetical 500 $\mu\text{g kg}^{-1}$ acrylamide level and thus are limited to the blanching
302 and frying conditions used in this study. As such, the THV mentioned should not be considered as
303 absolute. Because of the impact of final frying on acrylamide formation, an approach in which more
304 appropriate selection criteria of the raw material combined with informative advices given to consumers

1 305 and catering may contribute to safer French fries.

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3 306 The preliminary data obtained in this study and the threshold values concept presented, demonstrate
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5 307 that from a food safety point of view, a more optimal quality control could be adopted for incoming
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7 308 potatoes in order to guarantee reduced acrylamide contents in the final product. Agtron measurement
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10 309 after blanching and a two stage frying, or, measuring reducing sugars of the incoming product could
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12 310 provide a preventive tool for French fry industry to evaluate the acrylamide problem at the start of the
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15 311 production. It should be emphasized that implementing these alternatives of quality control in for
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17 312 instance a food safety management system on company level, would require the input of supplementary
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19 313 resources, having an impact on total production cost and cost-effectiveness of these possible mitigation
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22 314 tools.

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24 315 Since acrylamide formation is dependent on the surface area of the potato product and on the process
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26 316 conditions applied, the extrapolation of results for other type of potato products with different surface-to
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29 317 volume ratios, such as potato crisps, should not be considered.

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31 318 Moreover, due to the multiple pre and post-harvest factors that may impact the final amounts of the
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33 319 precursors in the raw material to acrylamide in French fries, this study should be repeated/validated
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36 320 throughout different seasons. Work is currently been carried out for the 2008 harvest season.

37 38 39 321 40 41 42 322 **Abbreviations used**

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45 323 DM, dry matter; FW, fresh weight; AA, acrylamide; RS, reducing sugars; THV, threshold value;
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48 324 USDA, United States Department of Agriculture.

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56
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7 331 editing of the manuscript.
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1 390 **Figure captions**

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4 391 Figure 1. Experimental setup used for the correlation study between reducing sugars in raw material,
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6 392 colour and acrylamide formation in French fries.

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12 394 Figure 2. Relation between USDA (I – after short frying test; II - after two stage frying) and acrylamide
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15 395 content (determined after two stage frying) in unblanched (filled square, solid line) and blanched (open
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17 396 square, broken line) French fries.

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23 398 Figure 3. Relation between Agtron (I – after short frying test; II - after two stage frying) and acrylamide
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26 399 content (determined after two stage frying) in unblanched (filled square, solid line) and blanched (open
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28 400 square, broken line) French fries.

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35 402 Figure 4. Relation between a* colour (I – after short frying test; II - after two stage frying) and
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37 403 acrylamide content (determined after two stage frying) in unblanched (filled square, solid line) and
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39 404 blanched (open square, broken line) French fries.

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46 406 Figure 5. Relation between reducing sugars content in raw potatoes and acrylamide content in French
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48 407 fries (after two stage frying) without blanching (filled square, solid line) and after blanching (open
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51 408 square, broken line).

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57 410 Figure 6. Relation between reducing sugars content in raw potatoes without blanching (filled square,
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1 411 solid line) and after blanching (open square, broken line) with acrylamide content in French fries (after
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3 412 blanching and two stage frying).
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Table captions

Table 1. Average dry matter (DM), reducing sugars content (RS) and acrylamide (AA) formation in French fries before and after blanching treatment for different potato varieties throughout storage. RS contents between brackets represent min and max values.

Table 2. Pearson correlation coefficients (R) between respectively entrance parameters (reducing sugars-raw material; colour-1 stage frying) and final parameters (reducing sugars-blanching raw material; colour-after blanching and two stage frying) and acrylamide (after blanching and two stage frying) levels in French fries.

Table 3. Threshold values determination for entrance parameters (reducing sugars-raw material; colour-after one stage frying) and final parameters (reducing sugars-blanching raw material; colour-after blanching and two stage frying), based on a hypothetical acrylamide limit of 500 $\mu\text{g kg}^{-1}$ and their application to samples of the present study regarding the acrylamide formation in French fries.

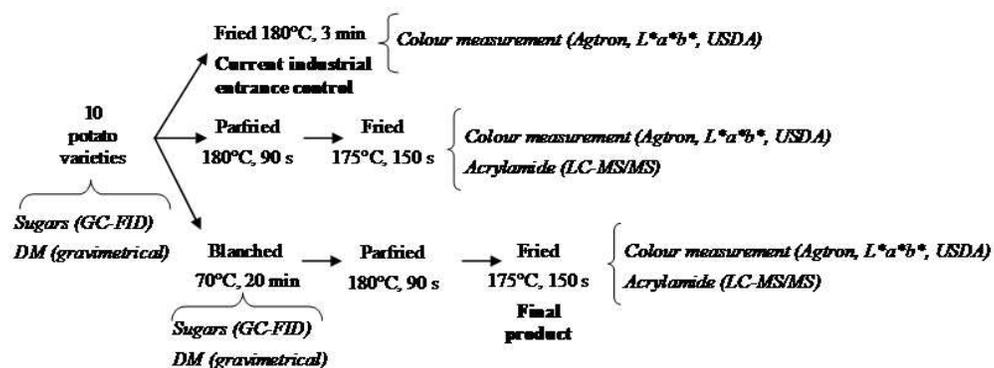


Figure 1. Experimental setup used for the correlation study between reducing sugars in raw material, colour and acrylamide formation in French fries.
213x84mm (96 x 96 DPI)

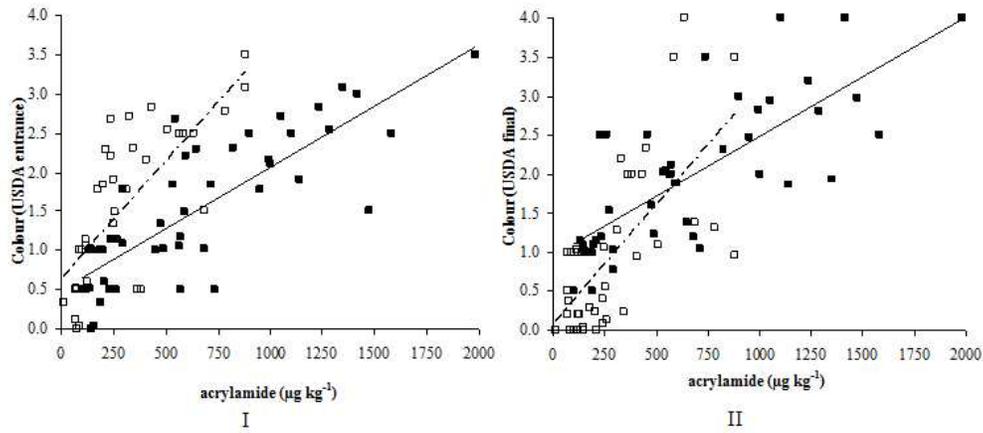


Figure 2. Relation between USDA (I – after short frying test; II - after two stage frying) and acrylamide content (determined after two stage frying) in unblanched (filled square, solid line) and blanched (open square, broken line) French fries.
200x94mm (96 x 96 DPI)

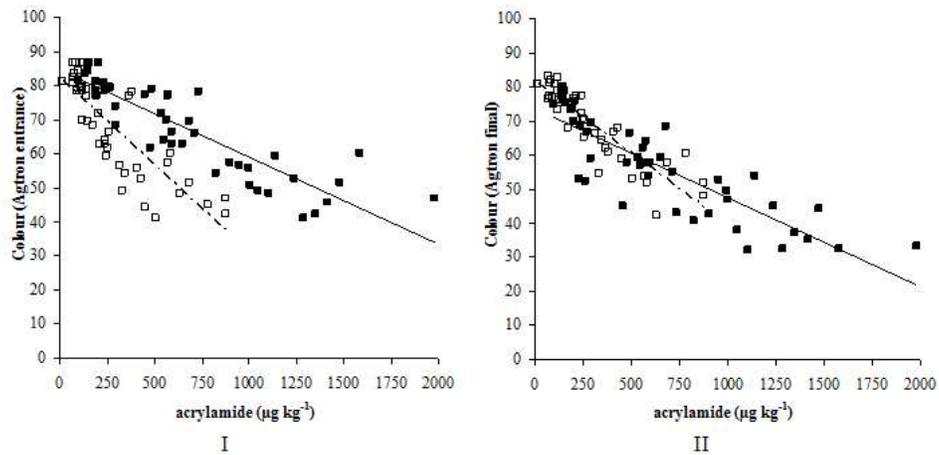


Figure 3. Relation between Agtron (I – after short frying test; II - after two stage frying) and acrylamide content (determined after two stage frying) in unblanched (filled square, solid line) and blanched (open square, broken line) French fries.
196x95mm (96 x 96 DPI)

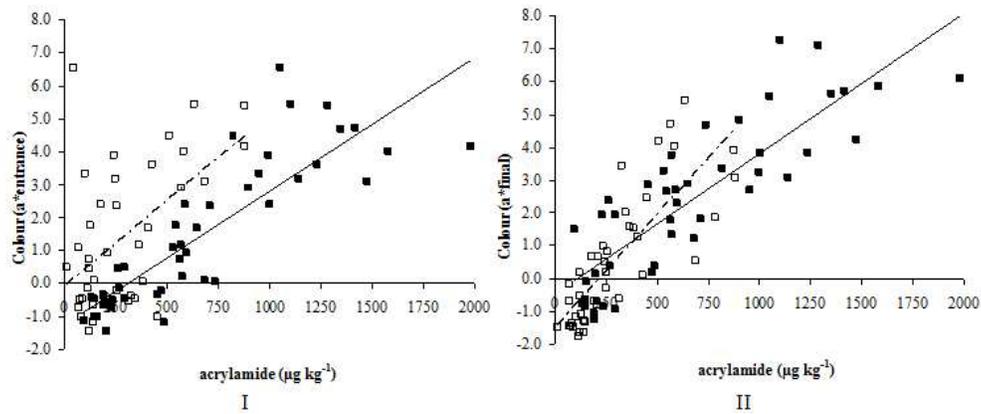


Figure 4. Relation between a* colour (I – after short frying test; II - after two stage frying) and acrylamide content (determined after two stage frying) in unblanched (filled square, solid line) and blanched (open square, broken line) French fries.
200x91mm (96 x 96 DPI)

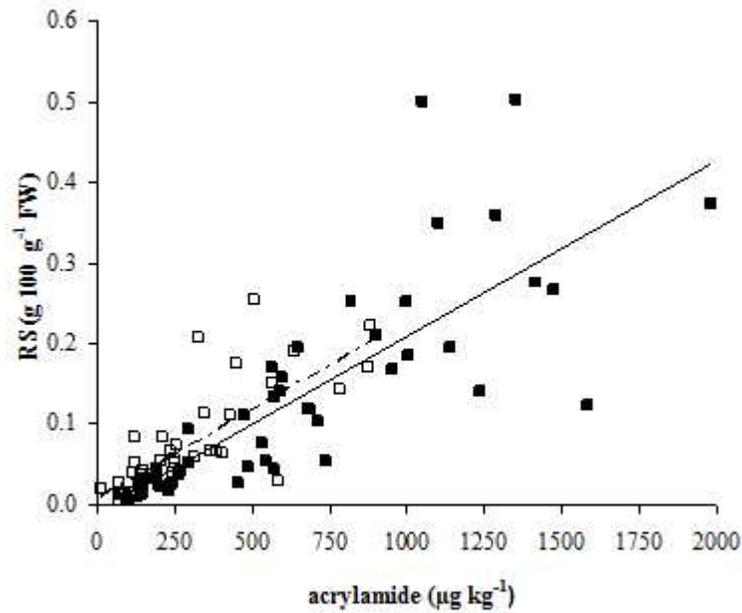


Figure 5. Relation between reducing sugars content in raw potatoes and acrylamide content in French fries (after two stage frying) without blanching (filled square, solid line) and after blanching (open square, broken line).
102x89mm (96 x 96 DPI)

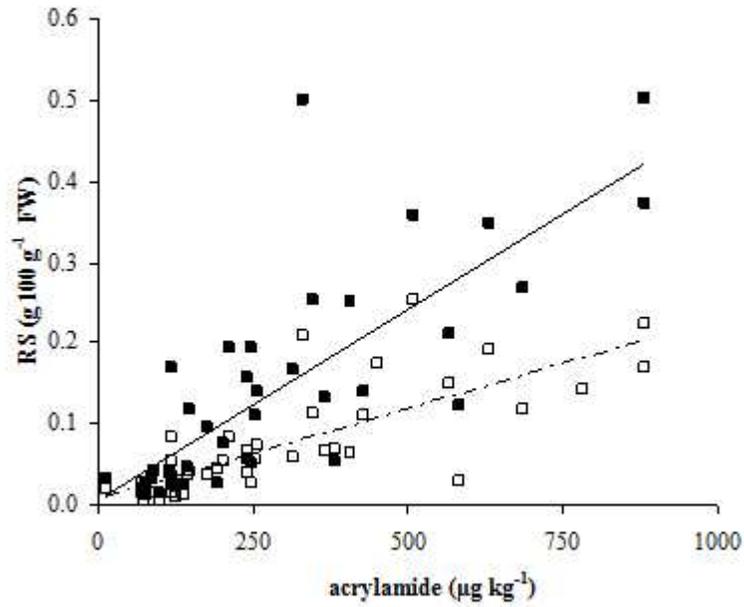


Figure 6. Relation between reducing sugars content in raw potatoes without blanching (filled square, solid line) and after blanching (open square, broken line) with acrylamide content in French fries (after blanching and two stage frying).
102x91mm (96 x 96 DPI)

	Before blanching treatment			After blanching treatment		
	DM	RS	AA	DM	RS	AA
	%	(g 100 g ⁻¹ FW)	(µg kg ⁻¹)	%	(g 100 g ⁻¹ FW)	(µg kg ⁻¹)
Maris Piper	20.7	0.36 (0.25-0.50)	1114	17.4	0.17	454
Asterix	19.4	0.34 (0.25-0.50)	1409	18.8	0.14	727
Bintje	20.9	0.21 (0.11-0.36)	716	18.5	0.13	305
Russet Burbank	20.5	0.16 (0.06-0.21)	900	17.4	0.08	375
Innovator	21.6	0.15 (0.13-0.19)	616	19.9	0.06	211
Agria	19.3	0.12 (0.08-0.17)	919	17.5	0.05	341
Victoria	16.6	0.06 (0.03-0.10)	534	15.3	0.03	73
Fontana	19.7	0.06 (0.03-0.14)	291	18.6	0.03	141
Lady Olympia	19.4	0.04 (0.02-0.05)	382	17.9	0.02	180
Markies	20.2	0.03 (0.01-0.03)	148	19.2	0.01	61

Table 1. Average dry matter (DM), reducing sugars content (RS) and acrylamide (AA) formation in French fries before and after blanching treatment for different potato varieties throughout storage. RS contents between brackets represent min and max values.
135x91mm (150 x 150 DPI)

	Parameter	R
Entrance	USDA	0.74 ^a
	Agtron	-0.83 ^a
	L*	-0.63 ^a
	a*	0.77 ^a
	b*	-0.46 ^b
	RS (g 100 g ⁻¹ FW)	0.72 ^a
	Fructose (g 100 ⁻¹ FW)	0.75 ^a
	Glucose (g 100 g ⁻¹ FW)	0.70 ^a
	Sucrose (g 100 g ⁻¹ FW)	0.00 ^b
	Final	USDA
Agtron		-0.88 ^a
L*		-0.59 ^a
a*		0.80 ^a
b*		-0.22 ^b
RS (g 100 g ⁻¹ FW)		0.78 ^a
Fructose (g 100 g ⁻¹ FW)		0.83 ^a
Glucose (g 100 g ⁻¹ FW)		0.65 ^a
Sucrose (g 100 g ⁻¹ FW)	0.29 ^b	

^ap < 0.01; ^bp < 0.05

Table 2. Pearson correlation coefficients (R) between respectively entrance parameters (reducing sugars-raw material; colour-one stage frying) and final parameters (reducing sugars-blached raw material; colour-after blanching and two stage frying) and acrylamide (after blanching and two stage frying) levels in French fries.
176x173mm (96 x 96 DPI)



	Threshold values	N ^o accepted samples	N ^o accepted samples and AA >500 $\mu\text{g kg}^{-1}$	N ^o rejected samples	N ^o rejected samples and AA <500 $\mu\text{g kg}^{-1}$	% Correctly categorized samples
Entrance	USDA <2.1	28	1	14	7	81
	RS <0.25 g 100 g ⁻¹ FW	33	2	6	1	92
	Agtron >57	31	2	11	5	83
Final	USDA <1.6	33	4	9	5	79
	RS <0.11 g 100 g ⁻¹ FW	34	2	8	2	90
	Agtron >61	33	1	9	2	93

Table 3. Threshold values determination for entrance parameters (reducing sugars-raw material; colour- after one stage frying) and final parameters (reducing sugars-blanching raw material; colour- after blanching and two stage frying), based on a hypothetical acrylamide limit of 500 $\mu\text{g kg}^{-1}$ and their application to samples of the present study regarding the acrylamide formation in French fries. 182x83mm (96 x 96 DPI)