Accepted Manuscript

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PII: S0956-7135(15)30250-4

DOI: 10.1016/j.foodcont.2015.10.028

Reference: JFCO 4706

To appear in: *Food Control*

Received Date: 22 June 2015

Revised Date: 7 October 2015

Accepted Date: 22 October 2015

Please cite this article as: Yang Y., Achaerandio I. & Pujolà M., Influence of the frying process and potato cultivar on acrylamide formation in French fries, *Food Control* (2015), doi: 10.1016/j.foodcont.2015.10.028.

Influence of the frying process and potato cultivar on acrylamide formation in ~~french~~ French fries

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Abstract

Acrylamide formation during the production of French fries is attributed to Maillard reactions from reducing sugars and asparagine and is dependent on the frying temperature. Low reducing sugars content in potatoes has been recommended to produce fried potato products. However, the influence of the complexity of the potato medium in the chemical reactions that promote the acrylamide formation during deep frying are not well understood. In this study, three potato cultivars (Kennebec, Red Pontiac and Agria) commonly used for fried potato products were evaluated to determine the relationships between the precursors of acrylamide in the fresh potato tubers and the properties of the fried potato strips with the acrylamide content after frying. Frying experiments were conducted at three conditions (time-temperature) to obtain French fries of similar visual colour. Acrylamide formation increased with frying temperature but different behaviour was observed between cultivars. For Red Pontiac, a remarkably increase in acrylamide content was found at 170ºC (~40 %) together with the increase in colour. However, lower oil uptake and higher moisture content was obtained as temperature increase. Significant positive correlations were observed between the acrylamide level and the reducing sugars and sucrose content on fresh potatoes (0.652, 0.699, $p \leq 0.01$, respectively). The acrylamide content obtained in Agria cultivar may be obtained from the hydrolysis of sucrose during the frying process. In fried potato strips, positive significant correlation was found between the shear force and acrylamide (0.749, $p \leq 0.01$). The significant correlations obtained between colour, and texture, colour and oil uptake and texture and acrylamide content indicate the intrinsic relationship between the properties of the fried potato strips and the acrylamide content.

~~Three potato cultivars (Kennebec, Red Pontiac and Agria) commonly used for fried potato products were selected to evaluate the effect of different frying conditions on acrylamide formation in French fries. The main objective was to determine the relationships between the precursors of acrylamide in the fresh potato tubers (reducing sugars and asparagine) and the properties of the fried potato strips (oil uptake, moisture content, colour and texture) with the acrylamide concentration after frying. Frying experiments~~

were conducted at 150, 170 and 190 ºC. The potato strips exhibited more acrylamide content, lower oil uptake, higher moisture content, darker colour, and greater hardness when the frying temperature was increased from 150 to 190 ºC. Significant positive relationships were observed between the acrylamide level and the asparagine, reducing sugars and sucrose contents, b*, Chroma and shear force and negative correlations with the oil uptake and L* in fried potato strips. In addition, the oil uptake presented significant positive correlations with the L* and H in French fries. However, these relationships were different between individual cultivars, especially for the Agria cultivar, which exhibited no correlation between the studied factors. This study clearly indicates the complex relationship of acrylamide formation with possible precursors in various potato cultivars.

Keywords: asparagine, colour, oil uptake, reducing sugars, sucrose, texture

1. Introduction

The potato (*Solanum tuberosum*) is one of the world's major agricultural crops and is consumed daily by millions of people from diverse cultural backgrounds (Pedreschi & Moyano, 2005). French fries have been a popular salty snack for 150 years, and their retail sales in the US are almost one-third of the total sales in this market (Garayo & Moreira, 2002).

Frying has been defined as the immersion of a food product in edible oil above the boiling point of water (Hubbard & Farkas, 1999), with colour, texture and flavour development. It is a complex process because of the two mass transfers in opposite directions within the material being fried; for starchy products, water and some soluble material escapes from the products and oil enters the food (Blumenthal & Stier, 1991). The reports of acrylamide intake indicate that fried potato products, bread and bakery products, coffee and breakfast cereals are the food commodities that contribute the greatest dietary acrylamide exposure (Vinci, Mestdagh, & Meulenaer, 2012). EFSA (2011) reported that the 95th percentiles of the acrylamide intake for adults and for children are estimated to range between 0.6-2.3 $\mu g.kg^{-1}$ bw/day and 1.5-4.2 $\mu g.kg^{-1}$ bw/day, respectively. Acrylamide is a neurotoxin in humans, and it has been considered to be a probable human carcinogen (Hogervorst, Schouten, Konings, Goldbohm, & Van den Brandt, 2007; Pedreschi, Kaack, & Granby, 2004; Hu, Xu, Fu, & Li, 2015). Researchers and industry need to find solutions to reduce or prevent acrylamide formation, despite the lack of legal limits for this contaminant, in foods, especially fried potato products.

The content of acrylamide (by-product of the Maillard reaction in food processed at a temperature > 120 ºC) is dependent on factors such as the cultivar, fertilization, storage, blanching, cooking temperature and time, and the amount of reducing sugars and free amino acids, such as asparagine, present in the potatoes (Marquez & Anon, 1986; Cheong, Hwang, & Hyong, 2005; Halford et al., 2012; Daniali, Jinap, Hanifah, & Hajeb, 2013). There have been several reports on reducing acrylamide formation, and these strategies were compiled in a "Toolbox" by Food Drink Europe

(http://www.fooddrinkeurope.eu/uploads/publications_documents/Toolboxfinal260911.pdf).

The reducing sugars and asparagine, as acrylamide precursors, are very important for reducing the acrylamide content in fried potato products (~~Palazoglu~~ Palazoğlu, Savran, & ~~Gokmen~~Gökmen, 2010). However, the relationship between the asparagine and reducing sugars concentrations in the fresh potatoes and the acrylamide formation during processing are surprisingly complicated. According to the report of Vinci et al. (2012), asparagine concentrations are relatively high compared to the reducing sugars content, which represents the limiting factor in acrylamide formation in fried potato products. In contrast, Shepherd et al. (2010) found that the asparagine and sugar concentrations contributed approximately equally to the acrylamide formation. In addition, Halford et al. (2012) suggested that when the sugar concentration was relatively high, acrylamide formation during processing was proportional to the sugar content, whereas when the sugar level was low, acrylamide formation was proportional to the asparagine content.

~~As one strategy to reduce acrylamide formation, the potato cultivar selection is very important~~ The selection of the potato cultivar is very important to reduce acrylamide formation. Some cultivars are more suitable than others for frying in strips, due to their large, long tubers and low reducing sugar content. The frying conditions produce dramatically affect the levels of acrylamide, as well as the browning, texture, and flavour development caused by the Maillard reaction (Mottram, Wedzicha, & Dodson, 2002; Stadler et al., 2002). The frying time and oil temperature should be controlled to reduce the acrylamide content, and the temperature should not exceed 170-175 ºC, as lower temperatures towards the end of the Maillard reaction may reduce acrylamide formation (Vinci et al., 2012). Longer frying periods may result in higher acrylamide contents.

During the frying process, oil is used as the heating medium and as an ingredient producing calorific products. Oil uptake is considered the major nutritional critical point of fried products because of the epidemic obesity prevalent in developed and even in developing countries caused by meals rich in fat (FAO, 2002). In addition, Zamora and Hidalgo (2008) and Capuano, Oliviero, Acar, Gokmen, and Fogliano (2010) indicated that lipid oxidation positively influences the formation of acrylamide. However,

other studies have not discovered any significant negative effect of the oil uptake on acrylamide formation. To date, there is still some confusion and misunderstanding regarding the influence of oil uptake on acrylamide formation. Due to health concerns, consumer preference for low-fat and fat-free products has been the driving force of studies to understand the oil uptake to control and reduce the oil uptake and acrylamide content while still retaining the desirable texture and flavour of fried potato products.

This study aimed to evaluate the influence of frying conditions on acrylamide formation and to investigate the existence of a relationship between acrylamide levels and the factors potentially involved in the formation of acrylamide, such as the frying temperature, reducing sugars, asparagine, moisture, oil uptake and instrumental sensory parameters (colour and texture) in three potato cultivars commonly used for fried products in Europe.

2. Materials and Methods

2.1. Sample preparation

In accordance with the report by Yang, Achaerandio, and Pujola (2015), potato tubers (*Solanum tuberosum*) of three cultivars (Red Pontiac, Kennebec and Agria) were selected. Tubers were commercialized in Spain and obtained from Mercabarna (Mercados de Abastecimientos de Barcelona SA, Barcelona, Spain). All potato cultivars were grown in Europe and had the same postharvest storage conditions prior to use. The dry matter content of all potato cultivars was greater than 200 $g \cdot kg^{-1}$. The flesh colour of the Red Pontiac and Agria cultivars was yellow, and the colour of the cv. Kennebec was white. The potatoes were stored at 8 ºC and 95% relative humidity. In our experiment, 8 kg of potatoes from the same industrial lot were classified by size. The mean weights of all the potato cultivars were similar, higher than 200 g. Potatoes were hand peeled and then cut into strips (1×1×6 ~~mm~~ cm) with a stainless steel slicer. A fraction of 200 g of potato strips were randomly selected for the frying process. Sunflower oil containing 65% oleic acid was used in the frying. The potato strips of each sample were

fried in an electrical fryer (Taurus, Spain) at the following temperature-time conditions: (i) 190 ºC for 160 s, (ii) 170 ºC for 240 s, (iii) 150 ºC for 330 s. The frying period was previously determined by the final colour of the frying strips. The final colour of the fried strips was fixed to standard 3 on the colour scale of the USDA standard for frozen French fries (USDA, 1988). The potato strips' mass to oil mass ratio (g/g) was 1:5. Each cultivar was fried in triplicate under the same frying conditions. After frying, portions of the samples were lyophilized using a Cryodos-45 freeze-drying instrument (Terrasa, Spain), packed in plastic bags and maintained at -20 ºC until further use. Another fraction of 200 g of fresh potato strips was homogenized and then the required weight was taken to undergo with the sugar and asparagine analysis.

2.2. Instrumental analysis of colour and texture

2.2.1. Colour

The colour of the potato strips was measured using a Minolta CR-400 colorimeter (Osaka, Japan) in the CIE lab space. The L* (lightness), a* (greenness [-] to redness [+]), and b* (blueness [-] to yellowness [+]) were recorded and evaluated. The parameters of hue angle (H°) and chroma (C) were calculated as $H^{\circ}=\tan^{-1}(b^*/a^*)$ and $C= (a^{*2}+b^{*2})^{1/2}$. Six measurements were taken for each experiment, and the results were expressed as the mean value ± standard deviation.

2.2.2. Texture analysis: Shear force and texture profile analysis

Shear force

The shear force of the samples was measured using a texture analyser (TAXT plus, Stable Microsystems, Surrey, UK), as described by Singh, Kaur, McCarthy, Moughan, and Singh (2008). The test conditions used for the measurement were pre-test speed 1 mm/s; test speed 1 mm/s; post-test speed 1 mm/s; target distance of 30 mm into the samples and trigger force of 2 g. Six potato strips were taken for each experiment, and the shear force (N) was expressed as the mean value ± standard deviation.

Texture profile analysis

Each potato strip was cut to a length of 10.0 mm using a knife. The texture profile analysis (TPA) was performed with the parameters set to pre-test speed 0.83 mm/s, test speed 0.83 mm/s and post-test speed 0.83 mm/s; a rest period of 5 s between the two cycles; and a trigger force of 5 g. The maximum extent of the deformation was 10% of the original length. According to the definitions of Szczesniak (1975) and Bourne (1978), the TPA values for hardness (N), cohesiveness (dimensionless), springiness (mm) and chewiness (N x mm) were calculated from the resulting force-time curve. Six potato strips were tested for each experiment, and the results were expressed as the mean value ± standard deviation.

2.3. Analysis of moisture content

The moisture content of the potato strips was measured by drying 5g of the homogenised samples in a convection oven until constant mass at 65 ºC. Analysis was conducted in triplicate for each individual experiment. The results were the mean of the triplicate experiments and expressed as $g \cdot kg^{-1}$.

2.4. Analysis of oil uptake

2 g of dried potato sample was put in a Soxhlet extractor for 4 h using petroleum ether. After extraction, the samples were dried for 30 min at 100 ºC. The oil content was calculated by the difference between the initial weight and the end weight of each sample, and the results were expressed as $g \cdot kg^{-1}$ (AOAC, 2005; Method 934.01).

2.5. Analysis of asparagine

Asparagine was determined according to the assay (K-ASNAM) procedure of Megazyme International 2014. Briefly, 1 g of the homogenised fresh potato sample was homogenized in 10 mL of water for 3 min. Following centrifugation (1000 rpm × 10 min, 4 ºC), the concentration of the clear supernatant was between 0.005 and 0.50 g/L. 0.1 mL sample solution, 0.02 mL glutaminase, and pH 4.9 buffer were mixed and incubated for 5 min at room temperature. Then, 1.6 mL distilled water, 0.3 mL buffer (pH 8.0)

196 and 0.2 mL NADPH were added, and the solution was mixed and incubated for 5 min at room
197 temperature. The reaction was started by the addition of 0.02 mL glutamate dehydrogenase suspension
198 and the solution was mixed, and the absorbance of the solutions (A_1) was read by a spectrophotometer at
199 340 nm after 5 min and at 1 min intervals until the absorbance remained the same, indicating the end of
200 the reaction. Then, 0.02 mL asparaginase was added, and the absorbance of the solutions (A_2) was read
201 after 5 min and at 1 min intervals until the absorbance is constant. The blank solutions include all the
202 reagents of the samples without the 0.1 mL of sample solution. The asparagine was calculated as [(A_1-
203 $A_2)_{sample} - (A_1\text{-}A_2)_{blank}$] × 0.4949. If the sample has been diluted during the preparation, the result must be
204 multiplied by the dilution factor. The results were expressed as $g \cdot kg^{-1}$ of fresh weight, and each sample
205 was analysed in triplicate.

206 2.6. Analysis of sugars

207 ~~Fresh samples (~~5 g~~)~~ of the homogenised sample were extracted by refluxing for 30 min with 40 ~~ml~~ mL of
208 70% ethanol. The extract was vacuum-filtered, and the filtrate was diluted to 50 mL with ethanol. A 5 mL
209 aliquot of the solution was passed through a Waters Sep-Pak C_{18} column and filtered (0.45 µm pore-size
210 membrane), and then 20 µL of each filtrate was injected into a Hewlett Packard series 1100 high-
211 performance liquid chromatograph (HPLC) equipped with a Beckman 110B injector and a Beckman
212 Refraction Index Detector (RID). The separation was performed using a Phenomenex Lunacolumn (250 x
213 4.6 mm i.d.), following (with a few modifications) the procedure of Hernandez, Gonzalez-Castro, Alba,
214 and Garcia (1998). The mobile phase consisted of acetonitrile/water (78:22, v/v), and the flow rate was
215 1.8 $mL \cdot min^{-1}$. Individual sugars (fructose, glucose and sucrose) were identified and quantified using
216 external standards. Each sample was analysed in triplicate. The sugar contents were expressed as $g \cdot kg^{-1}$ of
217 fresh weight.

218

219

220 2.7. Analysis of acrylamide

221 The determination of acrylamide was conducted following (with a few modifications) the procedure of
222 the gas chromatograph (PerkinElmer, 2004). 1 g of lyophilized powder was combined with 10 mL 0.1%
223 formic acid solution and mixed on a wrist action shaker for 20 min. The mixture was refrigerated for 40
224 min for easier removal of the top oil layer. A 3 mL aliquot of the clarified aqueous phase (beneath the oil
225 layer) was filtered through a 0.45 µm nylon syringe filter and stored for clean-up and analysis. The SPE
226 tube was preconditioned with 2 mL acetone, followed by 2 mL 0.1% formic acid, at the rate of one drop
227 per second, and the acetone and formic acid were discarded. 2 mL of the filtered extract solution was
228 subjected to solid-phase extraction (SPE) (CarboPrep^{TM} 200 tube, 6 mL, 500 mg) with only gravity flow.
229 The SPE tube was washed with 1.0 mL water and the solution was quickly passed through the tube.
230 Vacuum was used for up to 1 min to dry excess water from the tube. The acrylamide residue in the SPE
231 tube was eluted with 2 mL of acetone with using gravity only and collected for GC-FID analysis.

232 The GC analysis of the extract samples was performed on an AutoSystem gas chromatograph equipped
233 with a flame ionization detector (FID) (Hewlett Packard 5890 series II) following the procedure by Sun *et*
234 *al.* (2012). The column used was an Agilent HP-FFAP capillary (length=25 m, i.d.=0.2 mm, and
235 thickness=0.3 µm), and the analysis conditions were as follows: the initial column temperature was
236 settled at 100 ºC for 0.5 min, then raised at a gradient of 10ºC/min to 200 ºC; the temperatures of the
237 injector and detector were set to 250 and 260 ºC, respectively; helium was used as the carrier gas at a flow
238 rate of 1 mL/min and a splitless of 1 min, and the injection volume was 1 µm. The results were expressed
239 as $\mu g \cdot kg^{-1}$ of lyophilized weight (LW).

240 2.8. Statistics

241 The data reported was the mean of triplicate independent experiments. The variations were evaluated
242 through one-way analysis of variance (ANOVA) using Minitab 16 Statistical software (MINITAB Inc,
243 State College, PA, USA). Differences between mean values were evaluated using the HSD Tukey test

with a 95% confidence interval. Pearson's correlation analysis was carried out to study the relationships between variables.

3. Results and Discussion

3.1. Influence of frying temperature on acrylamide formation

It is well-known that commercial potato strip production prefers to use the cultivars with lower reducing sugar (glucose and fructose) and asparagine contents. Although an upper limit has not been specified for cultivars suitable for potato frying production, CIAA (2009) advised the use of potato cultivars with a reducing sugar content of less than 3 $g.kg^{-1}$ fresh weight for use in fried potato products. In this study, three cultivars were selected: one (Red Pontiac) with a reducing sugar content of more than 3 $g.kg^{-1}$ fresh weight and two (Agria and Kennebec) with contents of less than 3 $g.kg^{-1}$ fresh weight. The concentrations of the assumed precursors of acrylamide (glucose, fructose and asparagine) are shown in Table 1. The concentrations of glucose in the Red Pontiac and Kennebec cultivars were 3.14 and 1.26 $g.kg^{-1}$ fresh weight, while the fructose concentrations were 1.76 and 0.85 $g.kg^{-1}$ fresh weight, respectively. The contents of glucose and fructose in the Agria cultivar were the lowest of the three cultivars. The values of asparagine ranged from 2.03 to 3.21 $g.kg^{-1}$ fresh weight, which is in line with the values (0.15-4.58 $g.kg^{-1}$ fresh weight) reported for different cultivars by Vivanti, Finotti, and Friedman (2006).

The frying time and oil temperature should be controlled to avoid high acrylamide levels, and the temperature should not exceed 170-175 ºC (Vinci et al., 2012). Thus, in this study, 150, 170 and 190 ºC were selected for assessing the effect of temperature on acrylamide formation. The acrylamide levels of potato strips prepared by frying at 150, 170 and 190 ºC are shown in Figure 1; the contents for all tested cultivars ranged from 1975 to 5563 $\mu g.kg^{-1}$ LW for 150 ºC, 3124 to 5814 $\mu g.kg^{-1}$ LW for 170 ºC, and 4424 to 6035 $\mu g.kg^{-1}$ LW for 190 ºC, which are values slightly higher than those previously reported for fried potato products in other studies (Pedreschi et al., 2004; Pedreschi, Kaack, & Granby, 2006) because of the different frying conditions and potato cultivars. The lowest acrylamide content was found in the Kennebec cultivar. The acrylamide levels changes varied with the temperature and cultivar. As Figure

1.A shows, the acrylamide content steadily increased with the frying temperature from 150 to 190 ºC for the Kennebec cultivar; it significantly increased as the frying temperature increased from 150 ºC to 170 and 190 ºC for the Red Pontiac cultivar; and it slightly increased with the temperature for the Agria cultivar. Hence, a higher temperature results in a higher acrylamide level in fried potato products, in agreement with other studies (Palazoğlu, et al., 2010; Pedreschi et al., 2006), but the degree of increase was not the same for different potato cultivars, which was attributed to the different contents of the acrylamide precursors and moisture.

Correlations between the acrylamide in the fried potatoes and the concentrations of asparagine and sugars were investigated for all the tested cultivars together and separately for the individual cultivars and revealed some unexpected differences. There was a significant correlation between the asparagine concentration and acrylamide level ($r=0.423$, $p<0.05$) (Table 2), but no significant correlations were found for the individual cultivars. As Figure 2.A shows, the Kennebec cultivar, with the lowest acrylamide content, had a lower asparagine level; the asparagine content of Agria was the highest of the three cultivars tested, but its acrylamide level was not higher than the content of Red Pontiac, which is consistent with the report of Vinci et al. (2012), who reported that the asparagine concentration is generally in excess compared to the reducing sugar content in some cultivars, so that the reducing sugar content is the limiting factor in acrylamide formation.

The correlation between reducing sugar and acrylamide contents is also shown in Table 2. Overall, there was a significant correlation ($r=0.652$, $p<0.01$), but considering the individual cultivars, it was only found in Red Pontiac ($r=0.626$, $p<0.05$). The differences between the individual cultivars were more apparent when acrylamide was correlated with fructose and glucose concentrations. Overall there were significant correlations between fructose and acrylamide ($r=0.621$, $p<0.01$) and glucose and acrylamide ($r=0.663$, $p<0.01$), and a significant correlation within the three cultivars was only found in the Red Pontiac cultivar for fructose ($r=0.614$, $p<0.05$) and glucose ($r=0.615$, $p<0.05$). As Figure 2.B shows, the Red Pontiac, with the highest acrylamide content, generally contained the highest reducing sugar content, while the reducing

sugar content of Agria was the lowest of the three cultivars, but the acrylamide content was higher than that of Kennebec, which is not consistent with several studies (Marquez & Anon, 1986; Amrein et al., 2003) that reported significant correlations between the reducing sugar and acrylamide contents. Therefore, the mechanistic pathway of acrylamide formation is complex, and it is not possible to say whether this is the explanation for these contrasting correlations without more detailed kinetic studies of the acrylamide formation. However, it may provide the new evidence to prove the suggestions of Halford et al. (2012), who reported that when the sugar content was relatively high, the acrylamide formation was proportional to the sugar concentration.

There was a significant correlation between sucrose content and acrylamide formation ($r=0.699$, $p<0.01$). However, sucrose was not considered a precursor of acrylamide formation because the sucrose concentration was significantly correlated with reducing sugars ($r=0.610$, $p<0.01$), so it may not necessarily reflect a direct relationship. Sucrose has been shown to contribute to acrylamide formation, which may be due to the hydrolysis through an enzymatic, thermal or acid-catalysed reaction (Halford et al., 2012).

3.2. Relationship between acrylamide formation, oil uptake and moisture content

3.2.1. Oil uptake and acrylamide formation

The oil uptake is a complex mechanism that is not clearly understood, and the initial product structure, the interchanges between the product and the heating medium, and the variations in the product and oil properties are the factors that explain this phenomenon (Ziaiifar, Achir, Courtois, Trezzani, & Trystram, 2008). The oil uptake in the three cultivars after frying at different temperatures is shown in Figure 1.B. The oil uptake decreased as the frying temperature increased from 150 to 190 ºC for all tested cultivars, although this effect was more evident in previous studies (Moyano & Pedreschi, 2006; Pedreschi & Moyano, 2005). Increasing the temperature from 150 to 190 ºC significantly reduced the oil uptake only for the Kennebec cultivar, as the extents of reduction for the Red Pontiac and Agria cultivars were not great. This trend was similar to that of the acrylamide levels at different temperatures. The correlation

between the oil uptake and acrylamide formation was significantly negative ($r=-0.505$, $p<0.01$) in all analysed cultivars after frying. However, a much stronger and significant correlation was found in the Kennebec cultivar ($r=-0.781$, $p<0.01$). The crust formation during frying may promote lesser losses of water and then, acrylamide diffusion across the potato tissue may be possible. ~~weak correlations were found in the Red Pontiac ($r=-0.427$, $p=0.252$) and Agria ($r=-0.379$, $p=0.315$) cultivars~~. Oil uptake reduction is also very important when frying potato strips. Therefore, the relationship between the oil uptake and the acrylamide formation necessitates that we find an optimum frying condition to obtain lower levels of both acrylamide content and oil uptake.

3.2.2. Moisture content, oil uptake and acrylamide formation

The difference in the moisture content between the cultivars and temperatures was not great ~~(Figure 5)~~ because decreasing the temperature necessitates increasing the frying time, resulting in similar final moisture content. However, the moisture content slightly increased with the temperature from 150 to 190 ºC, ranging from 572 to 697 $g.kg^{-1}$, which was coincident with those reported by Pedreschi and Moyano (2005). Amrein, Limacher, Conde-Petit, Amadò, and Escher (2006) reported a strong effect of the moisture content on the activation energy of acrylamide formation, which explains why lower temperatures for longer times are known to yield lower acrylamide levels in the final product. ~~It was also reported that decreasing the moisture content tends to end of the frying process. The correlations between the moisture content and acrylamide level are shown in Table 2; the moisture content presented weak negative correlations with the acrylamide level in all cultivars ($r=-0.163$, $p=0.417$), but~~ From our results, strong correlations were found in the Kennebec ($r=0.928$, $p<0.01$) and Red Pontiac ($r=0.595$, $p<0.05$) cultivars.

Gamble, Rice, and Selman (1987) found that moisture loss and oil uptake are interrelated, and both are linear functions of the square root of the frying time. In addition, Ziaiifar et al. (2008) reported that the more water is removed from the surface, the more oil is absorbed. ~~The moisture content in this study is the final content after frying, and the higher the final moisture content, the less was lost~~. ~~The correlations~~

~~between the moisture content and oil uptake after frying at different temperatures were investigated for all tested cultivars (Table 2), and the correlation (r=-0.224, p=0.261) was negative but not significant. However,~~ A significant negative correlation was found in the Kennebec cultivar (r=-0.778, $p<0.05$), which is in agreement with the report by Southern, Xiaodong, and Farid (2004). As a result, the oil uptake tends to decrease as the final moisture content increases during frying, which is in agreement with other studies (Gamble et al., 1987; Ziaiifar et al., 2008). However, the results also showed that there may be a characteristic curve of oil uptake against moisture content, and the curves for the different cultivars may be distinct.

3.3. Correlations of acrylamide formation and oil uptake with instrumental sensory parameters: colour and texture

3.3.1. Colour, acrylamide formation and oil uptake

The colour values are shown in Figure 3. In our experiment, the final colour of the French fries was visually classified between the standard 2 and 3 (USDA, 1988). The L* and H values tended to decrease and the b* and C values increased compared to their original values in the Red Pontiac and Kennebec cultivars, but the change of colour in the Agria cultivar between the fresh and fried potato strips was slight, which may be due to the reducing sugar content in the fresh potatoes. L* tends to decrease as the frying temperature is increased from 150 to 190 ºC, which means that the potato strips get darker. b* refers to the yellowness, and b* and C (positively correlated with the colour parameters of a* and b*) tend to increase, which proves that the frying strips get more red and yellow as the frying temperature increases; the H value decreased as the frying temperature increased. However, Table 2 shows that the colour parameters presented significant correlations with the acrylamide content of the potato cultivars. The correlation in all cultivars between the L* value and acrylamide content was significant and negative (r=-0.586, $p<0.01$), while the b* and C values presented positive significant correlations with the acrylamide content for all tested cultivars (r=0.420 and 0.479, $p<0.05$, respectively). However, the H values showed no significant correlations with the acrylamide content in all cultivars. Furthermore, the

lightness of the frying strips decreased as the acrylamide formation increased, which was attributed to the potato strips getting darker as a result of Maillard reactions, while the changing of the C and H valued (C increased and H decreased) as the frying temperature increased is because of the Maillard non-enzymatic reaction development (Pedreschi et al., 2006).

The oil uptake vs. colour parameters in potato cultivars fried at 150, 170 and 190 ºC are shown in Table 2.

There is clear effect of the colour parameter values on the oil uptake in the cultivars: the L* and H values showed good correlations with the oil uptake ($r=0.738$ and 0.569, $p<0.01$, respectively); the b* and C values showed negative and no significant correlations with the oil uptake in all cultivars. ~~This shows that the colour of the frying strips gets darker as more oil is taken up.~~

3.3.2. Texture parameters, acrylamide formation and oil uptake

The textural changes in the potato cultivars fried at 150, 170 and 190 ºC are shown in Figure 4. Compared to the textural values of fresh potatoes (Table 1), the shear force, hardness and chewiness decreased significantly, and the changes in the springiness and cohesiveness were slight. The shear force and hardness decreased because of the starch gelatinization and lamella media solubilisation during frying (Andersson, Gekas, Lind, Oliveira, & Oste, 1994). The difference in the textural values between the different temperatures was not significant, which is attributed to the higher temperature necessitating a shorter frying time, affecting the final textural values.

Only the shear force of the textural parameters presented a positive significant correlation with the acrylamide content ($r=0.749$, $p<0.01$) ~~but a not significant and negative correlation ($r=-0.375$, $p=0.054$) with oil uptake in the cultivars (Table 2)~~. The negative and significant correlation of L* with the shear force was found in all cultivars after frying ($r=-0.648$, $p<0.01$). In addition, there were negative significant correlations between L* and the shear force in the Red Pontiac and Kennebec cultivars ($r=-0.777$ and -0.439, $p<0.05$, respectively).

Therefore, when frying at 190 ºC, the potato strips were harder and darker and contained less oil and higher acrylamide levels than potato strips fried at 150 ºC in all cultivars, which agreed with Pedreschi and Moyano. (2005).

4. Conclusions

The composition of the fresh potato cultivar is the primary factor in the formation of acrylamide. Frying temperature is also relevant. Frying potato strips at 190 ºC resulted in more acrylamide, less oil uptake, more moisture, and darker and harder strips than those fried at 150 ºC. However, apart from the reducing sugars and asparagine, there are other ~~factors~~ aspects affecting the acrylamide formation. In our ~~present~~ study, sucrose and oil uptake may play a role in the final concentration of acrylamide. ~~For the Agria cultivar with a lower reducing sugar content, the possible hydrolysis of sucrose during the frying process may cause acrylamide production~~. According to our results, fried strips at 170-190ºC, that contained moisture and oil uptake higher than 650 and 150 $g \cdot kg^{-1}$, respectively, may give rise to higher contents of acrylamide. However, for the cultivars with lower reducing sugars content (Agria), it may be possible that the hydrolysis of sucrose during the frying process lead to increase the acrylamide content. ~~Additionally, frying the potato strips at 190 ºC resulted in more acrylamide, less oil uptake, more moisture, and darker and harder strips than those fried at 150 ºC~~. The significant correlations obtained between colour, and texture, colour and oil uptake and texture and acrylamide content indicate the intrinsic relationship between the properties of the fried potato strips and the acrylamide content. Further studies are needed with potatoes that contain low sugar content to confirm these relationships and establish the possible limitations of the frying process, regarding the acrylamide content. On the other hand, the estimation of the acrylamide content on low sugar content potatoes from the instrumental properties of the fried potato strips may be a possibility.

~~The significant correlations of the lightness and shear force with the acrylamide content indicated that the darker and harder French fries contained higher acrylamide levels. A significant correlation between the~~

~~oil uptake and acrylamide content was found in all tested cultivars, possibly indicating that the contribution of the oil uptake to the formation of acrylamide should not be neglected~~.

Acknowledgments

This work was supported in part by the China Scholarship Council (File number. 201206990014).

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509

Table 1. Texture, asparagine and sugars content of fresh potato samples

Cultivar	Texture parameters					Asparagine ($g.kg^{-1}FW$)	Sugars ($g.kg^{-1}$ FW)		
	Shear force (N)	Hardness (N)	Springiness (mm)	Cohesiveness	Chewiness (N.mm)		Fructose	Glucose	Sucrose
Kennebec	31.22±2.34a	227.20±3.90a	0.61±0.10a	0.11±0.02b	15.41±1.37a	2.03±0.08c	0.85±0.02b	1.26±0.02b	0.87±0.05b
Red Pontiac	30.15±1.09a	265.31±5.62a	0.53±0.08a	0.15±0.01a	21.00±2.42a	2.54±0.13b	1.76±0.03a	3.14±0.15a	1.48±0.04a
Agria	35.40±2.16a	230.20±4.70a	0.54±0.10a	0.14±0.01ab	13.95±2.88a	3.21±0.04a	0.69±0.01b	0.69±0.01c	1.31±0.06a

Values are expressed as mean values ± standard deviations.
One-way balance ANOVA by Turkey's test was performed and the mean values with different small letters are significant in columns ($P < 0.05$).

Table 2. Pearson correlations between the studied factors

	Acrylamide	Oil uptake
Asparagine	0.423*	-
Fructose	0.621**	-
Glucose	0.663**	-
Sucrose	0.699**	-
Reducing sugar	0.652**	-
Oil uptake	-0.505**	-
Moisture	-0.163	-0.224
L*	-0.586**	0.738**
b*	0.420*	-0.026
C	0.479*	-0.007
H	-0.284	0.569**
Shear force	0.749**	-0.375

Significant values are expressed: *$p < 0.05$, **$p < 0.01$.

Figure captions

Figure 1. Acrylamide levels (A) and Oil uptake (B) of fried potato cultivars prepared by different temperatures. a-c: Means with different small letters are significant ($p<0.05$) in different cultivars at same temperature. A-C: Means with different capitals are significant ($p<0.05$) in different temperatures at same cultivar.

Figure 2. Acrylamide levels *vs*. asparagine (A) and Acrylamide levels *vs*. reducing sugar content (B) for fried potato cultivars prepared by different temperatures.

Figure 3. The colour parameters (L*, b*,C and H) of potato cultivars at different frying conditions. a-c: Means with different small letters are significant ($p<0.05$) in different cultivars at same temperature. A-D: Means with different capitals are significant ($p<0.05$) in different temperatures at same cultivar.

Figure 4. Textural analysis parameters for different potato cultivars (A/Kennebec; B/Red Pontiac; C/Agria) caused by different frying conditions.

Figure 1

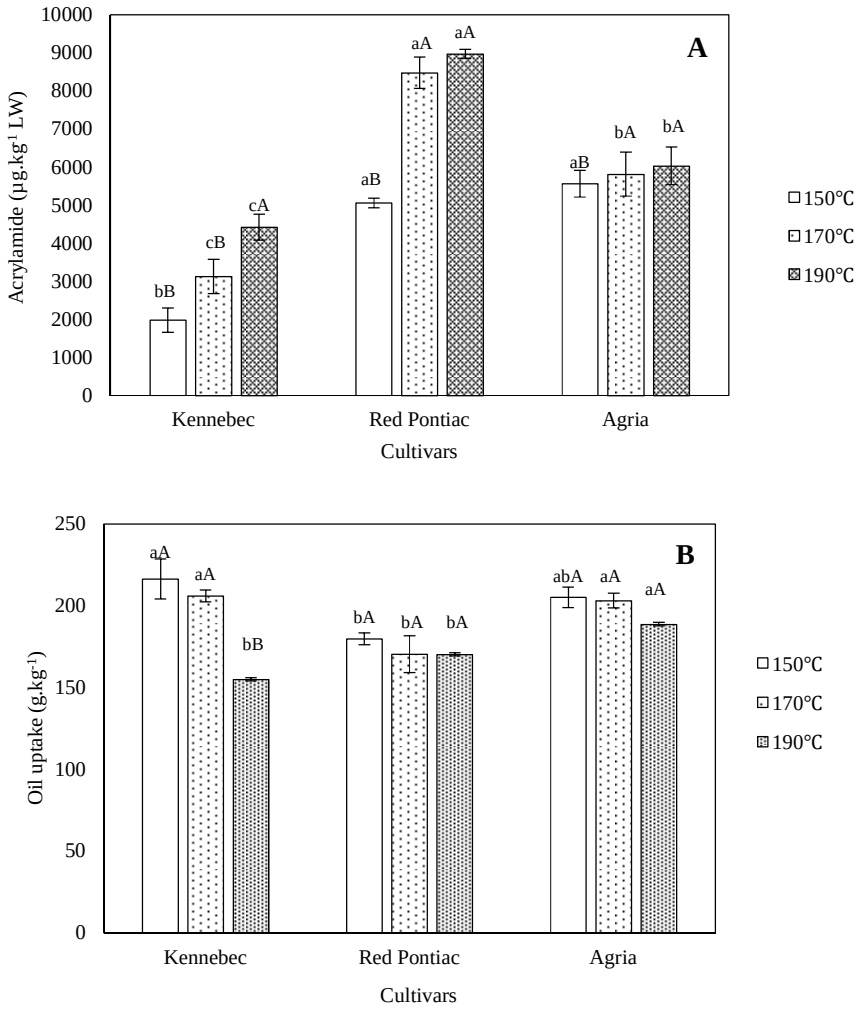

A
Acrylamide (µg.kg-1 LW)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
bB
cB
cA
aB
aA
aA
aB
bA
bA
Kennebec
Red Pontiac
Agria
Cultivars
150°C
170°C
190°C
B
Oil uptake (g.kg-1)
250
200
150
100
50
0
aA
aA
bB
bA
bA
bA
abA
aA
aA
Kennebec
Red Pontiac
Agria
Cultivars
150°C
170°C
190°C

Figure 2

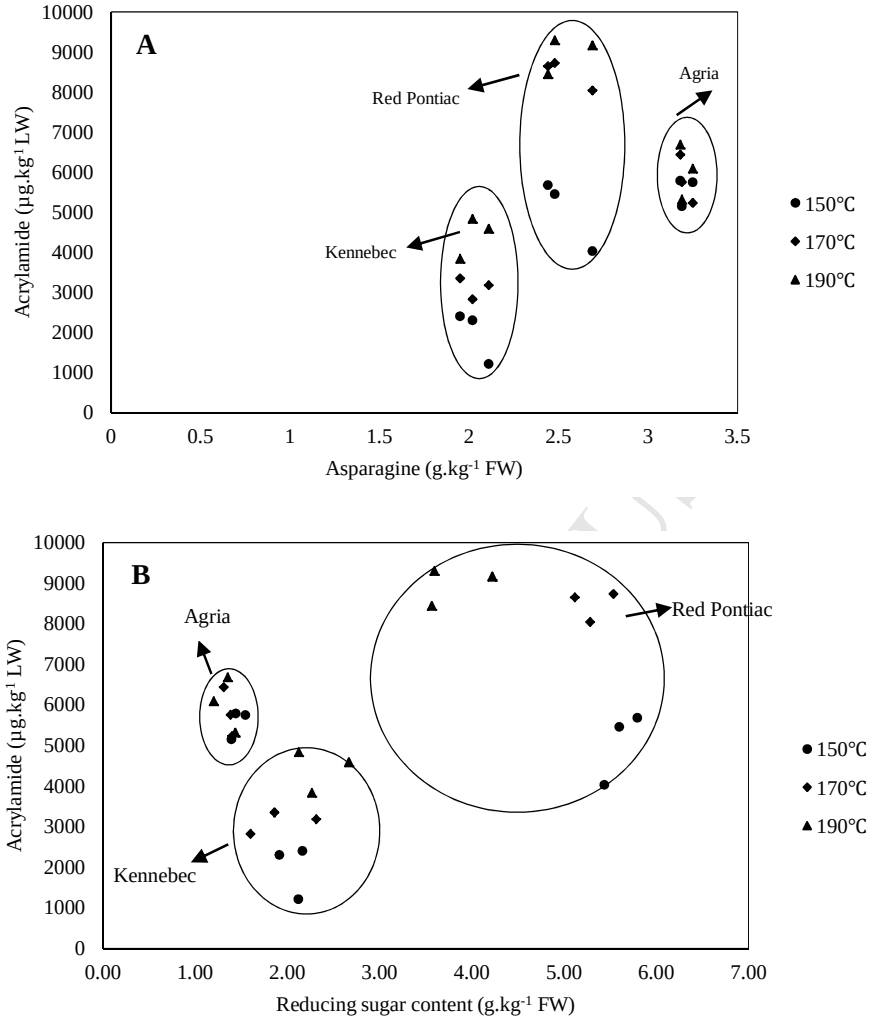

A
Red Pontiac
Agria
Kennebec
Acrylamide (µg.kg-1 LW)
Asparagine (g.kg-1 FW)
150°C
170°C
190°C
B
Agria
Red Pontiac
Kennebec
Acrylamide (µg.kg-1 LW)
Reducing sugar content (g.kg-1 FW)
150°C
170°C
190°C

Figure 3

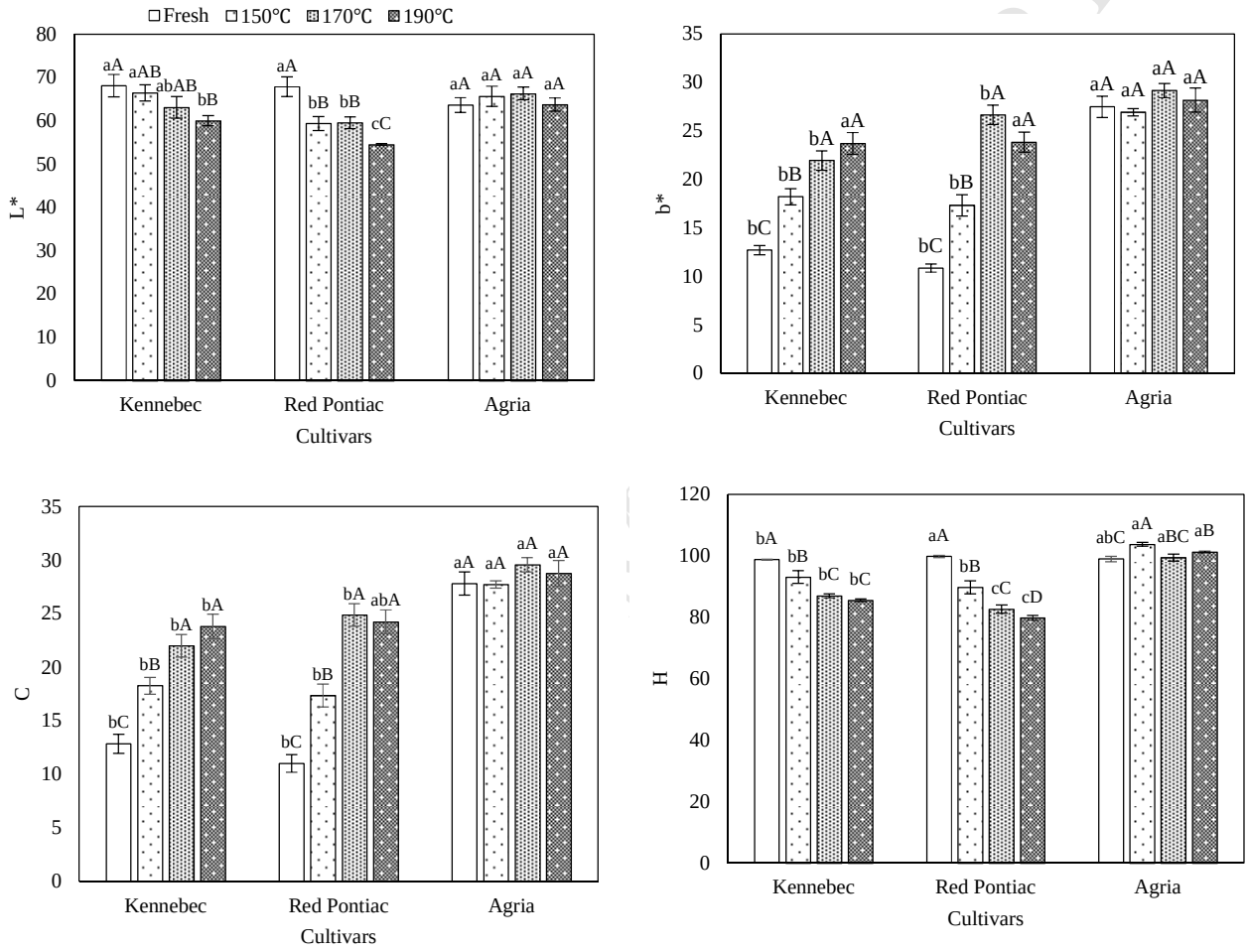
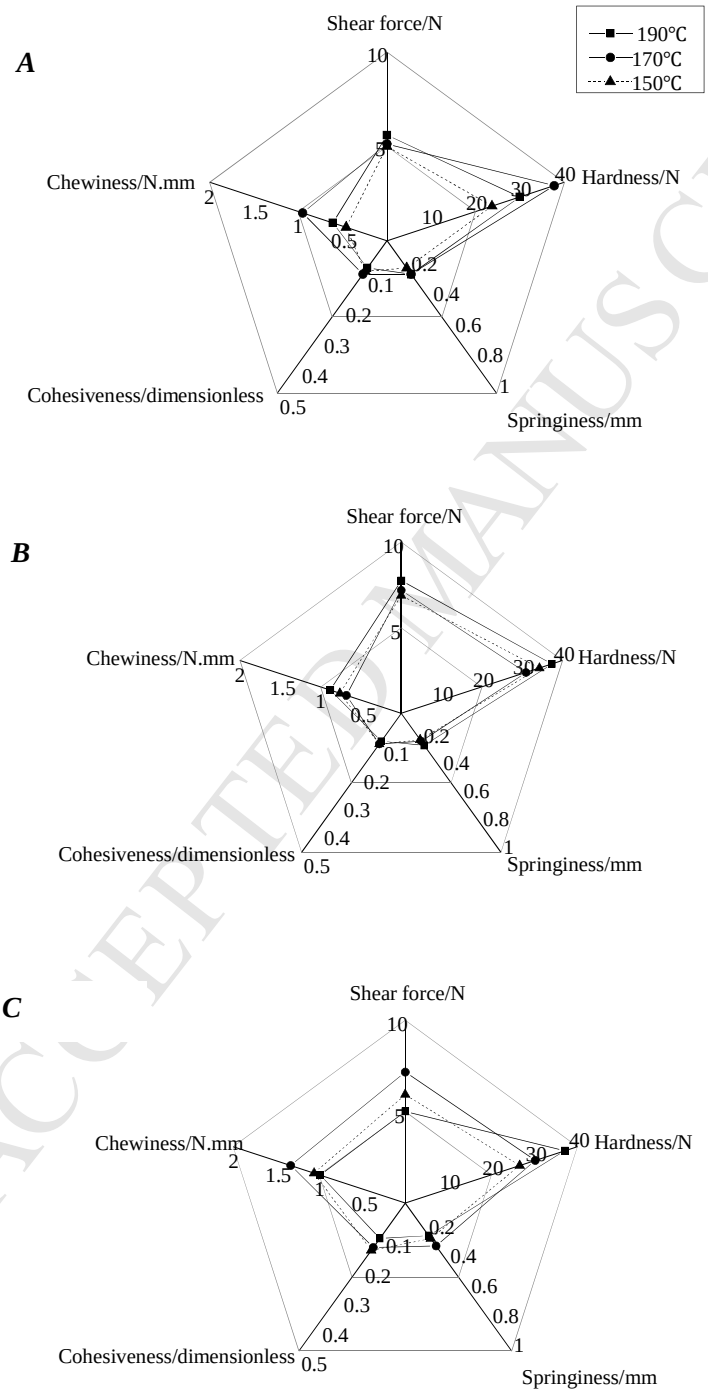

Fresh
150℃
170℃
190℃
L*
b*
C
H
Kennebec
Red Pontiac
Agria
Cultivars

Figure 4



Highlights

- French fries exhibited more acrylamide content when the frying temperature increased
- The hydrolysis of sucrose during frying may produce acrylamide
- The contribution of oil uptake in the acrylamide formation should not be neglected
- Colour and texture may be related to acrylamide in low sugar content potatoes