DTU Library

Formation and mitigation of acrylamide in oven baked vegetable fries

Nguyen, Khanh Hoang; Nielsen, Rikke Holm; Mohammadifar, Mohammad Amin; Granby, Kit

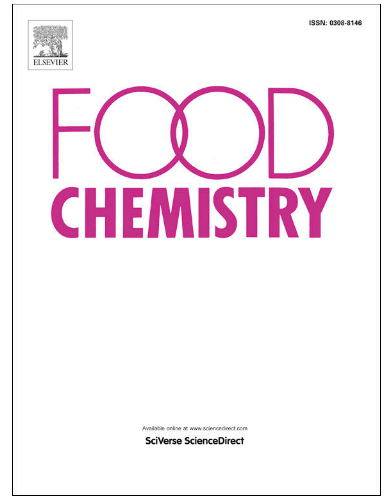
Published in:
Food Chemistry

Link to article, DOI:
10.1016/j.foodchem.2022.132764

Publication date:
2022

Document Version
Peer reviewed version

Journal Pre-proofs



Formation and mitigation of acrylamide in oven baked vegetable fries

Khanh Hoang Nguyen, Rikke Holm Nielsen, Mohammad Amin Mohammadifar, Kit Granby

PII: S0308-8146(22)00726-9
DOI: https://doi.org/10.1016/j.foodchem.2022.132764
Reference: FOCH 132764

To appear in: *Food Chemistry*

Received Date: 4 November 2021
Revised Date: 8 February 2022
Accepted Date: 19 March 2022

Please cite this article as: Nguyen, K.H., Nielsen, R.H., Mohammadifar, M.A., Granby, K., Formation and mitigation of acrylamide in oven baked vegetable fries, *Food Chemistry* (2022), doi: https://doi.org/10.1016/j.foodchem.2022.132764

Formation and mitigation of acrylamide in oven baked vegetable fries

Khanh Hoang Nguyen[*]*, Rikke Holm Nielsen, Mohammad Amin Mohammadifar, Kit Granby*

National Food Institute, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark

**Corresponding author: khng@food.dtu.dk*

Abstract

Investigation into oven baked sweet potato and carrot fries at various temperatures and times demonstrated the *in situ* formation of acrylamide in an exponential manner. High levels of acrylamide were found in these food items: up to 327 µg/kg for sweet potato baked at 190 °C for 14 min, and 99 µg/kg for carrot baked at 190 °C for 13 min. Risk assessment via Margin of Exposures estimation showed that consumption of these fries might pose adverse health effects to consumers from toddlers to adults, especially when the fries were prepared at high temperatures above 175 °C and for a long time. Raw ingredient blanching and immersion in acetic acid prior to preparation have been proven to greatly reduce acrylamide formation, up to 99%. It is recommendable to apply these techniques either at industrial or domestic cooking scales to ensure minimal health risk from dietary exposure to acrylamide.

Keywords

Acrylamide, vegetable fries, processing contaminants, food safety, mitigation

1. Introduction

Processing contaminants are harmful chemicals that can be generated during processing of food items (Curtis, Postles, & Halford, 2014; Li et al., 2021). These contaminants are naturally formed and ubiquitously present in many different types of food (Di Campi, Di Pasquale, & Coni, 2020; Li et al., 2021; Sadowska-Rociek & Surma, 2021; Tareke, Rydberg, Karlsson, Eriksson, & Törnqvist, 2002; Zelinkova & Wenzl, 2015). Some examples are polycyclic aromatic hydrocarbon formed during meat grilling or smoking, 3-monochloropropanediol found in acid-hydrolyzed vegetable proteins and soy sauce, or furan and alkyl-substituted furans generated by coffee roasting (Darwish, Chiba, El-Ghareeb, Elhelaly, & Hui, 2019; Jang & Koh, 2020; Park, Jo, & Lee, 2021). Another prime example of processing contaminants is acrylamide which can be found in potato fries, breakfast cereals, toasted bread, etc. (Claus, Carle, & Schieber, 2008; Granby et al., 2008; Pedreschi, Kaack, & Granby, 2004, 2006). In terms of formation mechanism, acrylamide is generated as a product of the Maillard reactions (Mottram, Wedzicha, & Dodson, 2002; Stadler et al., 2002). Consequently, the contaminant can be generated in foods that are prepared at high temperatures above 120 °C and low moisture (atmospheric pressure), especially those with high amounts of reducing sugars and asparagine (EFSA CONTAM Panel, 2015).

Firstly reported in foods in 2002 (Tareke et al., 2002), acrylamide is still a global concern due to its ubiquity and potential toxicity to humans (F. Fernández, Pardo, Coscollà, & Yusà, 2022; Liao et al., 2022). Acrylamide is metabolized in the liver to the genotoxic epoxide glycidamide. It has been categorized as probably carcinogenic to humans (Group 2A) by the International Agency for Research on Cancer (IARC, 1994). A two year study on mice and rats treated with acrylamide-containing drinking water performed by the United States National Center for Toxicological Research found cancer in several organs including lung, Harderian gland, forestomach, mammary and ovary of studied mice (Beland et al., 2013). In a comprehensive report published by the European Food Safety Agency (EFSA) in 2015, acrylamide was identified with genotoxicity, carcinogenicity, neurotoxicity, and reproductive toxicity (EFSA CONTAM Panel, 2015) Based on the genotoxic findings, EFSA CONTAM Panel selected acrylamide benchmark dose lower bound ($BMDL_{10}$) values of 0.17 mg/kg b.w. per day for neoplastic effects in mice and concluded that the human margins of exposure (MoEs) indicate a concern for neoplastic effects based on animal evidence.

Because of its potential adverse health effects, various types of food have been examined and regulatory precautions have been implemented to limit human dietary exposure to acrylamide (European Commission, 2017b). As more scientific findings came to light, the presence of acrylamide has been confirmed in more and more food items. For instance, acrylamide was detected in infant foods, breakfast cereals, and breads and bakery products purchased in U.S.A (Abt et al., 2019); or in biscuits purchased from Polish or Spanish markets (Mesías, Morales, & Delgado-Andrade, 2019; Michalak, Czarnowska-Kujawska, & Gujska, 2019). In 2019, on top of the foods well-known for containing this chemical (e.g. potato fries, coffee, etc.), the European Commission has released a recommendable non-exhaustive list of other foods for acrylamide monitoring (European Commission, 2019). Among these also entailed vegetable fries which have emerged recently as a popular alternative to potato fries. Since fries made from vegetables such as carrot or sweet potato have just gained traction among consumers lately, not so many studies have investigated the potential of processing contaminants formed in these food items including acrylamide. Because many other vegetables also contain reducing sugars, a key precursor of acrylamide in potato products, it is expected that the respective vegetable fries can also generate acrylamide (Breitling-utzmann & Hankele, 2019). However, limited studies have been performed on other root vegetable products. It is possible that the same knowledge about potato products does not directly apply to them. For instance, in contrast to potato or pumpkin crisps, it was reported that blanching showed very limited effects on acrylamide reduction in carrot crisps (Mesías, Delgado-Andrade, & Morales, 2019b). Therefore, it is essential to gather more insights into the formation, and more importantly, the mitigation approach for acrylamide in root vegetable products. Against these backgrounds, this study aims to investigate the formation of acrylamide in oven baked vegetable fries such as sweet potato or carrot, explore mitigation approaches, and subsequently estimate the risk of consuming these products, either without or after application of mitigation measures.

2. Materials and methods

2.1. Vegetable fries preparation

Whole Bolero carrot and Beauregard sweet potato were purchased from a local supermarket in the Greater Copenhagen area in February 2020. The vegetables were peeled then thoroughly rinsed under running water for 1 min. Afterward, a French fries cutter (Börner Rot-Gelb, Germany) was used to cut the vegetable into pieces of 0.8 x 0.8 x 5 cm. In order to simulate homemade oven baked fries, a recipe has been formulated based on various homemade recipes found online: 1 kg of vegetable fries was thoroughly mixed with 42 g of olive oil, 8.85 g of fine salt, and 1.17 g of ground black pepper (Bauer, 2020; Bittman, 2018). The fries were evenly distributed on a baking tray on top of a baking paper (circa 20 pieces per tray, allowing the adequate distance between each fry) before baking at different temperature and time conditions. A preliminary study was carried out to decide the specific temperature and time combination for each type of vegetable fries (Section 3.1). After each batch of fries, the whole batch was thoroughly homogenized and stored at -18 °C until analysis.

2.2. Chemicals and standards

Acrylamide (99.9%), and acetonitrile were purchased from Sigma-Aldrich Fluka (St. Louis, MO, USA); Acrylamide-d3 (>98%) was purchased from Polymer Source Inc. (Dorval, QC Canada); Formic acid (>98%) was obtained from Merck (Darmstad, Germany); Mini-UniPrep polypropylene filter vials (0.45 µm pore size) was purchased from Whatman Inc. (Clifton, NJ, USA). Stock solutions and working standard solutions of acrylamide and acrylamide-d3 (1 mg/mL and 10 µg/mL) as well as calibration standards (2-500 ng/mL) were prepared in water and kept at -18°C until use.

2.3. Physical properties measurement of the baked fries

The baked fries were measured for their surface color using a colorimeter (Minolta Chroma Meter CR-200, Japan). From each batch, three fries were randomly selected and the color measurements were performed on their upper surface (the side facing upward during the baking process) at each end and in the middle of the fries. A TA.XT Plus Texture analyzer (Stable Micro Systems, UK) was implemented to measure the texture profiles of the fries hardness and crispiness (fracturability) using an aluminum cylinder probe (50 mm diameter). The texture analyzer was performed in compression test mode using a test speed of 2 mm/sec and a trigger force of 0.049 N.

2.4. Acrylamide analysis

Acrylamide analysis was performed according to Nguyen et al., 2022 (Nguyen, Fromberg, Duedahl-Olesen, Christensen, & Granby, 2022) with minor modifications. A 3 g portion of homogenized sample was weighed into a 50 mL polypropylene conical tube and spiked with 150 µL of d_3-acrylamide internal standard (10 µg/mL). Acrylamide was then extracted by 30 mL of Milli-Q water using an Ultra Turrax Janke and Kunkel T25 homogenizer(IKA®-Werke, StaufenGermany) at 10000-12000 rpm for 2 min. After centrifuging the sample for 20 min at 3500 rpm (Multifuge X3 FR, Thermo Fisher Scientific), a 2 mL aliquot of the upper aqueous phase was transferred to an Eppendorf vial and frozen at -18 °C. Afterward, the partly defrosted samples were centrifuged (Hermle Z 216 MK) for 10 min at 14000 rpm. A 1 mL portion of the upper aqueous phase was used for SPE clean-up by an automated sampler (Gilson Acpec XI, Gilson Company Inc., Middleton, MI, USA) equipped with Isolute Multimode SPE cartridges (bed weight 300mg, Biotage, Uppsala, Sweden). After conditioning with acetonitrile and Milli-Q-water, 0.5 mL of sample was loaded on the SPE cartridge and led to waste. Another 0.4 mL of sample was loaded and the eluate collected into a Mini-UniPrep vial and the Mini-UniPrep polypropylene filter 0.45 µm was applied. Afterward, the filtered sample was analyzed using LC-MS/MS.

The LC-MS/MS system consisted of an ultra-high performance liquid chromatography (Ultimate 3000, Thermo Fisher Scientific, USA) coupled to a triple quadrupole mass spectrometer (Evoq Elite, Bruker, USA). Chromatography separation was achieved on a Kinetex Pentafluorophenyl column (2.6 µm x 3 mm x 100 mm, Phenomenex,Værløse, Denmark) with 0.1 % formic acid in Milli-Q water at 0.2 mL/min. Positive ESI mode was applied at capillary voltage 3.5 kV, cone and heated probe temperature 350°C. The transitions *m/z* 72.3>55.3 and 72.3>54.3 were used for acrylamide (quantification and qualification transitions, respectively) while *m/z* 75.3>58.3 was used for detection of the internal standard acrylamide-d3. The calibration standards for acrylamide ranged between 2 to 500 ng/mL and were run before and after every 10-15 samples.

2.5. QA/QC

Acrylamide concentration could deviate largely between different baking batches due to various factors such as where the individual fries stick was cut from e.g. close to the vegetable skin or to their core, or the dynamic of acrylamide reaction formation, etc. To minimize experimental and analytical deviations, each baking condition was carried out in three batches and double LC-MS/MS determination was performed for each sample. The fries were analyzed within two weeks after they were frozen. The acrylamide analytical method used in this study has been accredited since 2002 with method validations and proficiency tests performed on several matrices including potato fries and vegetable crisps. All proficiency test results were in very good agreement with assigned values from proficiency test providers (internal data).

Additionally, a recovery experiment was done on sweet potato and carrot fries to check the method performance on these matrices. Each matrix was spiked with acrylamide at 1500 µg/kg and good recoveries were obtained: 101% for sweet potato fries and 97% for carrot fries.

2.6. Risk assessment

Since acrylamide is a toxic chemical, it is important to perform a risk assessment of the population via dietary exposure – the main exposure source of acrylamide. This could be done via estimation of margin of exposure (MoE).

The MoE and daily intakes were calculated using the following equation:

$$Daily\ exposure\ = \frac{C \times consumption}{Body\ weight}$$

$$MoE = \frac{Benchmark\ dose\ lower\ bound\ (BMDL)}{Daily\ exposure}$$

Where C is the average concentration of acrylamide in oven-baked fries in this study before or after mitigation measures. The consumption data used for the exposure assessment has been derived from the "French fries and potato fried" category in EFSA's Comprehensive Database since such information for alternative fries like sweet potato or carrot are very limited (EFSA). The estimation was performed in four age groups: Toddlers (1-3 years old), Other children (3-10 years old), Adolescents (10-18 years old), and Adults (18-65 years old). Their corresponding body weight was assumed to be 20, 40, 55, and 70 kg, respectively. The benchmark dose level (BMDL) was 170 µg/kg body weight/day (EFSA CONTAM Panel, 2015).

2.7. Statistical analysis

Statistical analysis and data visualization were performed using OriginPro 2021 (OriginLab ©, USA). The confidence level was set at 95%. Linear regression at 95% confidence level on natural log transformed data was used to assess whether the formation of acrylamide in sweet potato and carrot fries follows exponential functions of baking time. Spearman rank correlation test was performed to investigate the correlation between physical parameters of the fries versus either baking time or temperature at 95% confidence level.

3. Results and discussion

3.1. Preliminary study on baking temperature and time conditions

In 2017, the European Commission published mitigation measures for the presence of acrylamide in foods (European Commission, 2017b). Specifically, French fries and other deep-fried or oven-fried potato products should be carried out at 160-175 ºC when frying and 180-220 ºC when using an oven. However, lower temperatures could be used when the oven fan mode is being implemented. According to Matthäus et al., the optimum moisture content of potato French fries ranges between 38 and 45% to ensure the right level of crispiness without drying out the products too much (Matthäus, Haase, & Vosmann, 2004). Since not so much information and cooking instructions are available for vegetable fries, we have adapted the "ideal" oven-bake temperature and moisture contents of vegetable French fries in this study from those of potato fries. A preliminary study was carried out to find out the required baking times for either sweet potato fries or carrot fries to reach the water content of 40% at three different temperatures: 160, 175, and 190 °C. The temperature was chosen to reflect the recommended baking temperature, as well as home cooking scenarios where slightly higher or lower temperature would be applied due to e.g., personal preferences, discrepancies between set and actual oven temperature, etc.. It took slightly less time for the carrot fries to reach 40% moisture content than sweet potatoes (Table S1). Specifically, the required times for sweet potato fries were 20, 15, and 12 at 160, 175, and 190 °C, respectively. Those values for carrot fries were 17, 14, and 11 min. Based on these observations, different temperature-time combinations were designed to investigate the formation of acrylamide in sweet potato and carrot fries (Figure 1A and 1B). Each type of fries was investigated at three temperatures (160, 175, and 190 °C) and at each temperature three baking times were used (time to reach 40%

water content and time to reach 40% water content ± 2 minutes). The three level of baking times at each temperature was chosen to mimic various consumers' preferences for their fries: slightly crispy, crispy, and extra crispy.

3.2. Acrylamide formation in oven baked sweet potato and carrot fries

Previous studies have shown that acrylamide can rapidly form in fried potato products, in which reducing sugars and asparagine are the main precursors (Mariotti et al., 2015; Pedreschi et al., 2006). Since both sweet potato and carrot contain these precursors at high levels, it is expected that acrylamide will also be formed in these types of fries (Breitling-utzmann & Hankele, 2019; Hou, He, Hu, & Wu, 2019; Kaack, Nielsen, Christensen, & Thorup-Kristensen, 2001). Figure 2A illustrates the levels of acrylamide formed in sweet potato fries at different baking times and temperatures. It was obvious that acrylamide concentrations increased as a function of both baking time and temperature. For instance, up to 327 µg/kg (mean concentration) of acrylamide was found in sweet potato fries prepared at 190 °C for 14 min while only one-tenth of that concentration was measured in the fries prepared at 160 °C for 18 min. A similar trend was observed in carrot fries: baking at 190 °C for 13 min produced an acrylamide concentration up to 99 µg/kg while only 5 µg/kg was detected in samples baked at 160 °C for 15 min (Figure 2B). The observed levels of acrylamide in sweet potato fries were somewhat similar to what has been observed by EFSA in both baked and deep-fried potato fries (mean concentrations around 250 µg/kg) (EFSA CONTAM Panel, 2015). On the other hand, carrot fries showed 3 to 5 times lower concentrations than sweet potato fries in this study, and also lower than potato fries as reported by EFSA. While no data is available for acrylamide in carrot fries, some studies have demonstrated higher levels of acrylamide in carrot crisps. For instance, up to 224 µg/kg of acrylamide was detected in laboratory produced carrot crisps (Mesías, Delgado-Andrade, & Morales, 2019a) or even as high as 958 µg/kg in commercial ones purchased in Spain (Mesías, Delgado-Andrade, et al., 2019b).

In terms of reaction kinetics, it has been reported that acrylamide formed exponentially in various products under frying or baking conditions (Breitling-utzmann & Hankele, 2019; Granby et al., 2008). To investigate whether acrylamide formed in baked sweet potato and carrot fries in the same manner, the acrylamide concentrations were transformed using natural logarithm then linear regression was applied on these transformed data as a function of time at individual baking temperatures. In this cases, a observed linearity means the formation of acrylamide is exponential. The regression results are shown in Figures 3A and 3B. In the case of sweet potato, the exponential formation of acrylamide was not very prominent at 160 °C but can be observed quite clearly at 175 and 190 °C. It is possible that at 160 °C, the lower heating conditions (and by that lower acrylamide levels) made it difficult to differentiate the acrylamide exponential formation from the triplicate baking series variation. For carrot fries, high R^2 values (greater than 0.97) for the regressions were observed at all investigated temperatures. These observations imply that the formation of acrylamide in oven baked sweet potato and carrot fries was also an exponential function of baking time, especially at high temperature. To confirm this conclusion, a batch of carrot fries was baked at 175 °C for 18 minutes, two minutes more than the required time stated in our experiment design. As expected, the newly obtained data points fit very well into the regression model which explained the acrylamide concentration as an exponential function of baking time (Figure 3B).

3.3. Physical properties of oven baked fries and their relations to acrylamide concentration

The measured color parameters of sweet potato and carrot fries were expressed in luminosity L*, *a**, and *b** according to CIELAB color space. The detailed color measurements for each type of fries at various time and temperature conditions were shown in Table S2. Previously, Pedreschi et al., 2006 found correlations between the color parameters L* and *a** for potato fries. Such correlations were not observed in this study (Spearman rank test, $p > 0.05$), possibly because both raw sweet potato and carrot fries were already exhibited quite vibrant colors. This indicates that it might not be possible for quick screening of acrylamide in these fries purely based on the colorimetric investigation.

It was hypothesized that the high temperature baking over an extended time would result in the formation of low hardness high crispiness fries, as well as a high level of acrylamide. However, there was no correlation (Spearman rank test, $p > 0.05$) found between acrylamide concentration and crispiness for neither sweet potato nor carrot fries. Meanwhile, a slight negative correlation could be observed between hardness and acrylamide content in carrot fries (Spearman rank test, $p = 0.04$, Spearman correlation = -0.54).

3.4. Mitigation of acrylamide in oven baked sweet potato and carrot fries

Previous studies on acrylamide mitigation in potato products (European Commission, 2017a; Friedman & Levin, 2008; Mariotti et al., 2015) have identified several techniques that could be employed to reduce the formation of acrylamide: immersion in water, blanching, immersion in organic acids (e.g. citric acid or acetic acid), and addition of antioxidants (such as black pepper, rosemary, oregano or pimento extracts). Among those techniques, the latter three have shown greater acrylamide reduction efficiency than immersion in water, albeit by different mechanisms (Hedegaard, Granby, Frandsen, Thygesen, & Skibsted, 2008; Jung, Choi, & Ju, 2003; Pedreschi et al., 2004). Since the formation of acrylamide in carrot and sweet potato fries is also exponential and dependent on temperature and baking time, it is likely that such fries prepared in a typical household might have a high level of acrylamide. This is because the control of baking time and temperature in households is not very precise in comparison with industrial processes. On top of that, there might be cases where consumers prefer to bake their fries for longer and/or at higher temperatures to achieve a high degree of crispiness. Therefore, two mitigation strategies that are easily applicable for both domestic and industrial preparation of fries have been investigated: blanching and acetic acid (vinegar) immersion. Blanching was performed in a temperature-controlled water bath at 50, 60, or 70 °C for 40 min. Immersion in acetic acid was performed by soaking fries in white vinegar (5% acetic acid) at a ratio of 1:10 (fries:vinegar, w/w) at room temperature for 15 and 30 min. Both sweet potato and carrot fries from mitigation experiments, together with corresponding control samples, were baked at 175 °C for 22 min. The extended baking time was deliberately chosen to ensure a high acrylamide formation in the control samples, hence facilitating the distinction of acrylamide reduction at different conditions.

It could be observed from Figures 4A and 4C that blanching was very effective in acrylamide reduction, and the reduction rates increased as the water temperature increased. Additionally, the effect of blanching was also observed at different degrees for the two types of fries in this study. Specifically, for sweet potato the acrylamide reduction rates were estimated at 77%, 87%, and 99% when the fries were blanched at 50, 60, and 70 °C, respectively. For carrot fries, these values were 53%, 83% and 84%, respectively. In a similar manner to blanching, acetic acid immersion showed greater effects on sweet potato (Figure 4B and 4D). Approximately 90% of acrylamide was mitigated in sweet potato fries after 15 min immersion while this figure for carrot fries was 73%. Interestingly, prolonged immersion in acetic acid did not lead to further reduction of acrylamide. It is possible that the rather high amount of acetic acid provided full acrylamide reduction potential within a short amount of time. In short, both blanching and immersion in acetic acid showed very high levels of acrylamide reduction. Both techniques also worked better on sweet potato than carrot fries.

3.5. Estimation of dietary acrylamide intake before and after mitigation measures

For a genotoxic and carcinogenic compound like acrylamide, where the ALARA principle (As low as reasonably achievable) applies, a MoE above 10000 is considered of low health concern (EFSA CONTAM Panel, 2015).

The MoE values for estimation of human exposure to acrylamide via home baked carrot and sweet potato fries' consumption before applying mitigation approaches are presented in Table 1. It was obvious that in all scenarios of consumption, the MoE values for sweet potato were under 10000 in all age groups, indicating a health risk. In regard to the carrot exposure, the estimated MoEs demonstrated a potential health risk for all age groups under both median and 95th percentile scenarios when consuming carrot fries baked for a rather long time: 160 °C for 19 mins, 175 °C for 14 or 16 mins, and 190 °C for 11 or 13 min. Most of the average consumption scenario for carrot fries prepared at 175 °C for 12 min, or at 190 °C for 9 min showed MoEs greater than 10000. A safe MoE was observed for all age groups in both average and 95th percentile scenarios for carrot fries baked at 160 °C for either 15 minutes or 17 minutes.

In general, without any mitigation applied, both carrot and sweet potato fries posed a health risk to consumers, except for carrot fries prepared at low temperature and for a short amount of time. In order to evaluate how the proposed mitigation approaches affect the exposure risk of acrylamide in vegetable fries, MoE values were also estimated for both types of fries which were previously blanched at 70 °C for 40 min. As discussed above, this was the condition providing the highest acrylamide reduction rate and highly applicable in domestic cooking. The calculated MoEs (data not shown) indicated that after blanching, in most scenarios the fries are "safe" to consume with a MoE higher than 10000. Specifically, only carrot fries prepared at 175 °C for 16 min and 190 °C for 13 min showed concerning MoEs smaller than 10000 in 95th percentile consumption in all groups. Additionally, toddlers would also be exposed to acrylamide at a concerning level when consuming carrot fries prepared at 190 °C in the average consumption scenario, even when blanching was applied.

Nevertheless, it was obvious that blanching at 70 °C for 40 minutes prior to baking greatly reduced the health risk associated with acrylamide exposure via carrot and sweet potato fries consumption. Therefore, it is recommended that blanching or a combination of both blanching and immersion in acetic acid should be performed when preparing vegetable fries from fresh ingredients, either in an industrial or domestic setting.

4. Conclusion

In this study, the formation of acrylamide in oven baked sweet potato and carrot fries was investigated at different baking temperatures and times. It was apparent that acrylamide formed in these types of fries exponentially and the acrylamide content increased as a function of both temperature and baking time. The highest amounts of this chemical were found in fries prepared at the highest temperature and longest time conditions: 327 µg/kg for sweet potato baked at 190 °C for 14 min, and 99 µg/kg for carrot baked at 190 °C for 13 min. Risk assessment estimation indicated that consumption of baked sweet potato could pose a health risk for all age groups regardless of consumer age group, baking temperature, or baking time. Similarly, the consumption of carrot fries also leads to potential health risks in many scenarios, especially when the fries were prepared at a high temperature and for a long time. Consequently, there is a need to mitigate the formation of acrylamide in these food items. Both blanching and immersion in acetic acid showed great reductions in acrylamide. However, both techniques worked better on sweet potato than carrot. It is recommended that either blanching, immersing in acidic solutions or a combination of the techniques should be applied during the preparation of sweet and potato fries to ensure the food safety of vegetable fries.

Reference

Abt, E., Robin, L. P., McGrath, S., Srinivasan, J., DiNovi, M., Adachi, Y., & Chirtel, S. (2019). Acrylamide levels and dietary exposure from foods in the United States, an update based on 2011-2015 data. *Food Additives and Contaminants - Part A Chemistry,* *Analysis, Control, Exposure and Risk Assessment*, *36*(10), 1475–1490. https://doi.org/10.1080/19440049.2019.1637548

Bauer, E. (2020). Oven Baked Sweet Potato Fries. Retrieved February 1, 2020, from https://www.simplyrecipes.com/recipes/oven_baked_sweet_potato_fries

Beland, F. A., Mellick, P. W., Olson, G. R., Mendoza, M. C. B., Marques, M. M., & Doerge, D. R. (2013). Carcinogenicity of acrylamide in B6C3F(1) mice and F344/N rats from a 2-year drinking water exposure. *Food and Chemical Toxicology : An International Journal Published for the British Industrial Biological Research Association*, *51*, 149–159. https://doi.org/10.1016/j.fct.2012.09.017

Bittman, M. (2018). Sweet Potato Fries. Retrieved February 1, 2020, from https://cooking.nytimes.com/recipes/1014647-sweet-potato-fries

Breitling-utzmann, C. M., & Hankele, S. (2019). Formation of acrylamide in vegetable crisps - Influence of processing conditions and reducing sugars. *Deutsche Lebensmittel-Rundschau*, *115*(September).

Claus, A., Carle, R., & Schieber, A. (2008). Acrylamide in cereal products: A review. *Journal of Cereal Science*, *47*(2), 118–133. https://doi.org/10.1016/j.jcs.2007.06.016

Curtis, T. Y., Postles, J., & Halford, N. G. (2014). Reducing the potential for processing contaminant formation in cereal products. *Journal of Cereal Science*, *59*(3), 382–392. https://doi.org/10.1016/j.jcs.2013.11.002

Darwish, W. S., Chiba, H., El-Ghareeb, W. R., Elhelaly, A. E., & Hui, S. P. (2019). Determination of polycyclic aromatic hydrocarbon content in heat-treated meat retailed in Egypt: Health risk assessment, benzo[a]pyrene induced mutagenicity and oxidative stress in human colon (CaCo-2) cells and protection using rosmarinic and ascorbic ac. *Food Chemistry*, *290*, 114–124. https://doi.org/10.1016/j.foodchem.2019.03.127

Di Campi, E., Di Pasquale, M., & Coni, E. (2020). Contamination of some foodstuffs marketed in Italy by fatty acid esters of monochloropropanediols and glycidol. *Food Additives and Contaminants: Part A*, *37*(5), 753–762. https://doi.org/10.1080/19440049.2020.1725146

EFSA. (2021). Comprehensive European Food Consumption Database. Retrieved October 14, 2021, from https://www.efsa.europa.eu/en/data-report/food-consumption-data#the-efsa-comprehensive-european-food-consumption-database

EFSA CONTAM Panel. (2015). Scientific Opinion on acrylamide in food. *EFSA Journal*, *13*(6). https://doi.org/10.2903/j.efsa.2015.4104

European Commission. (2017a). Commission Regulation (EU) 2017/2158: establishing mitigation measures and benchmark levels for the reduction of the presence of acrylamide in food. *Official Journal of the European Union*, *2017*(315), 24–44. https://doi.org/http://eur-lex.europa.eu/pri/en/oj/dat/2003/l_285/l_28520031101en00330037.pdf

European Commission. (2017b). Commission Regulation (EU) 2017/2158 of 20 November 2017 establishing mitigation measures and benchmark levels for the reduction of the presence of acrylamide in food. *Official Journal of the European Union*, (L 304), 24–44.

European Commission. (2019). Commission Recommendation (EU) 2019/1888 of 7 November 2019 on the monitoring of the presence of acrylamide in certain foods. *Official Journal of the European Union*, (L 290), 31–33.

F. Fernández, S., Pardo, O., Coscollà, C., & Yusà, V. (2022). Exposure assessment of Spanish lactating mothers to acrylamide via human biomonitoring. *Environmental Research*, *203*(August 2021). https://doi.org/10.1016/j.envres.2021.111832

Friedman, M., & Levin, C. E. (2008). Review of methods for the reduction of dietary content and toxicity of acrylamide. *Journal of Agricultural and Food Chemistry*, *56*(15), 6113–6140. https://doi.org/10.1021/jf0730486

Granby, K., Nielsen, N. J., Hedegaard, R. V., Christensen, T., Kann, M., & Skibsted, L. H. (2008). Acrylamide–asparagine relationship in baked/toasted wheat and rye breads. *Food Additives and Contaminants: Part A*, *25*(8), 921–929. https://doi.org/10.1080/02652030801958905

Hedegaard, R. V., Granby, K., Frandsen, H., Thygesen, J., & Skibsted, L. H. (2008). Acrylamide in bread. Effect of prooxidants and antioxidants. *European Food Research and Technology*, *227*(2), 519–525. https://doi.org/10.1007/s00217-007-0750-5

Hou, Y., He, W., Hu, S., & Wu, G. (2019). Composition of polyamines and amino acids in plant-source foods for human consumption. *Amino Acids*, *51*(8), 1153–1165. https://doi.org/10.1007/s00726-019-02751-0

IARC. (1994). Acrylamide. *IARC Monographs*, *60*, 389. Retrieved from http://www.inchem.org/documents/iarc/vol60/m60-11.html

Jang, Y., & Koh, E. (2020). Assessment of estimated daily intake of 3-monochloropropane-1,2-diol from soy sauce in Korea. *Food Science and Biotechnology*, *29*(12), 1665–1673. https://doi.org/10.1007/s10068-020-00832-5

Jung, M. Y., Choi, D. S., & Ju, J. W. (2003). A novel technique for limitation of acrylamide formation in fried and baked corn chips and in french fries. *Journal of Food Science*, *68*(4), 1287–1290. https://doi.org/10.1111/j.1365-2621.2003.tb09641.x

Kaack, K., Nielsen, M., Christensen, L. P., & Thorup-Kristensen, K. (2001). Nutritionally important chemical constituents and yield of carrot (Daucus carota L.) roots grown organically using ten levels of green manure. *Acta Agriculturae Scandinavica Section B: Soil and Plant Science*, *51*(3), 125–136. https://doi.org/10.1080/09064710127616

Li, C., Li, C., Yu, H., Cheng, Y., Xie, Y., Yao, W., … Qian, H. (2021). Chemical food contaminants during food processing: sources and control. *Critical Reviews in Food Science and Nutrition*, *61*(9), 1545–1555. https://doi.org/10.1080/10408398.2020.1762069

Liao, K.-W., Chang, F.-C., Chang, C.-H., Huang, Y.-F., Pan, W.-H., & Chen, M.-L. (2022). Associating acrylamide internal exposure with dietary pattern and health risk in the general population of Taiwan. *Food Chemistry*, *374*(November 2021), 131653. https://doi.org/10.1016/j.foodchem.2021.131653

Mariotti, M., Cortés, P., Fromberg, A., Bysted, A., Pedreschi, F., & Granby, K. (2015). Heat toxicant contaminant mitigation in potato chips. *LWT - Food Science and Technology*, *60*(2), 860–866. https://doi.org/10.1016/j.lwt.2014.09.023

Matthäus, B., Haase, N. U., & Vosmann, K. (2004). Factors affecting the concentration of acrylamide during deep-fat frying of potatoes. *European Journal of Lipid Science and Technology*, *106*(11), 793–801. https://doi.org/10.1002/ejlt.200400992

Mesías, M., Delgado-Andrade, C., & Morales, F. J. (2019a). Alternative food matrices for snack formulations in terms of acrylamide formation and mitigation. *Journal of the Science of Food and Agriculture*, *99*(4), 2048–2051. https://doi.org/10.1002/jsfa.9354

Mesías, M., Delgado-Andrade, C., & Morales, F. J. (2019b). Risk/benefit evaluation of traditional and novel formulations for nacking: Acrylamide and furfurals as process contaminants. *Journal of Food Composition and Analysis*, *79*(December 2018), 114–121. https://doi.org/10.1016/j.jfca.2019.03.011

Mesías, M., Morales, F. J., & Delgado-Andrade, C. (2019). Acrylamide in biscuits commercialised in Spain: A view of the Spanish market from 2007 to 2019. *Food and Function*, *10*(10), 6624–6632. https://doi.org/10.1039/c9fo01554j

Michalak, J., Czarnowska-Kujawska, M., & Gujska, E. (2019). Acrylamide and thermal-processing indexes in market-purchased food. *International Journal of Environmental Research and Public Health*, *16*(23). https://doi.org/10.3390/ijerph16234724

Mottram, D. S., Wedzicha, B. L., & Dodson, A. T. (2002). Acrylamide is formed in the Maillard reaction. *Nature*, *419*(6906), 448–449. https://doi.org/10.1038/419448a

Nguyen, K. H., Fromberg, A., Duedahl-Olesen, L., Christensen, T., & Granby, K. (2022). Processing contaminants in potato and other vegetable crisps on the Danish market: levels and estimation of exposure. *Journal of Food Composition and Analysis*, *108*(January), 104411. https://doi.org/10.1016/j.jfca.2022.104411

Park, S. hyun, Jo, A., & Lee, K. G. (2021). Effect of various roasting, extraction and drinking conditions on furan and 5-hydroxymethylfurfural levels in coffee. *Food Chemistry*, *358*(November 2020), 129806. https://doi.org/10.1016/j.foodchem.2021.129806

Pedreschi, F., Kaack, K., & Granby, K. (2004). Reduction of acrylamide formation in potato slices during frying. *LWT - Food Science and Technology*, *37*(6), 679–685. https://doi.org/10.1016/j.lwt.2004.03.001

Pedreschi, F., Kaack, K., & Granby, K. (2006). Acrylamide content and color development in fried potato strips. *Food Research International*, *39*(1), 40–46. https://doi.org/10.1016/j.foodres.2005.06.001

Sadowska-Rociek, A., & Surma, M. (2021). A survey on thermal processing contaminants occurrence in dark craft beers. *Journal of Food Composition and Analysis*, *99*(November 2020), 103888. https://doi.org/10.1016/j.jfca.2021.103888

Stadler, R. H., Blank, I., Varga, N., Robert, F., Hau, J., Guy, P. A., … Riediker, S. (2002). Acrylamide from Maillard reaction products. *Nature*, *419*(6906), 449–450. https://doi.org/10.1038/419449a

Tareke, E., Rydberg, P., Karlsson, P., Eriksson, S., & Törnqvist, M. (2002). Analysis of acrylamide, a carcinogen formed in heated foodstuffs. *Journal of Agricultural and Food Chemistry*, *50*(17), 4998–5006. https://doi.org/10.1021/jf020302f

Zelinkova, Z., & Wenzl, T. (2015). The Occurrence of 16 EPA PAHs in Food – A Review. *Polycyclic Aromatic Compounds*, *35*(2–4), 248–284. https://doi.org/10.1080/10406638.2014.918550

Highlights for the manuscript: "Formation and mitigation of acrylamide in oven baked vegetable fries"

- Acrylamide can form in oven baked sweet potato and carrot fries at high levels
- Acrylamide formation increased exponentially as a temperature and baking time function
- Margin of Exposure estimation revealed potential adverse health effect in many age groups when consuming sweet potato or carrot fries
- Blanching or acid immersion of raw ingredients can greatly reduce acrylamide formation, up to 99%

CRediT author statement

Khanh Hoang Nguyen: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Data Curation, Writing – Original Draft, Writing – Review & Editing, Visualization, Project administration

Rikke Holm Nielsen: Methodology, Formal analysis, Data Curation, Writing – Review & Editing

Mohammad Amin Mohammadifar: Resources, Data Curation, Writing – Review & Editing.

Kit Granby: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing – Review & Editing, Supervision, Project administration.