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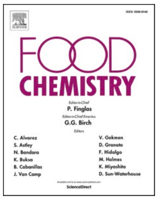

Formation and mitigation of acrylamide in oven baked vegetable fries

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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.

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

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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 × 0.8 × 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, Fromberg, Duedahl-Olesen, Christensen, and 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 10,000–12,000 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 14,000 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 300 mg, 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 × 3 mm × 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 and 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, 2021). 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 °C when frying and 180–220 °C 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 (Fig. 1A and B). 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 min). 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). Fig. 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 (Fig. 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

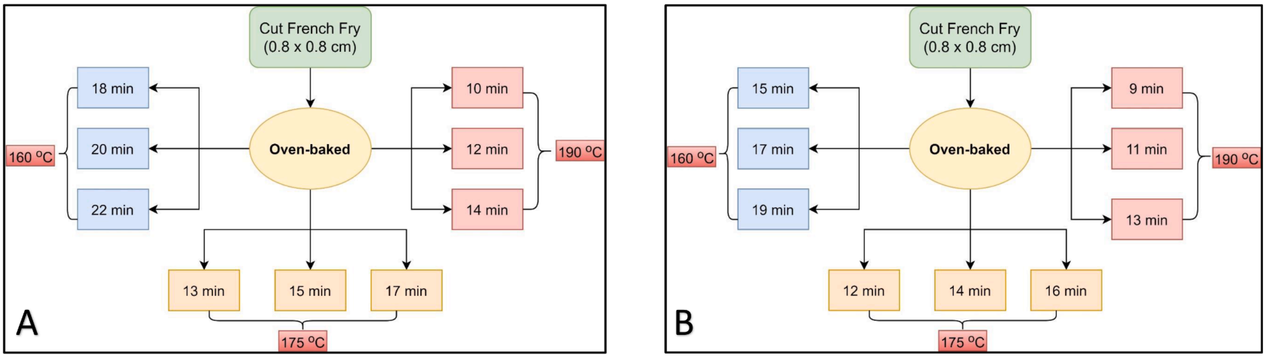

Fig. 1. Experimental set up for oven baking of (A) sweet potato and (B) carrot fries at different times and temperatures.

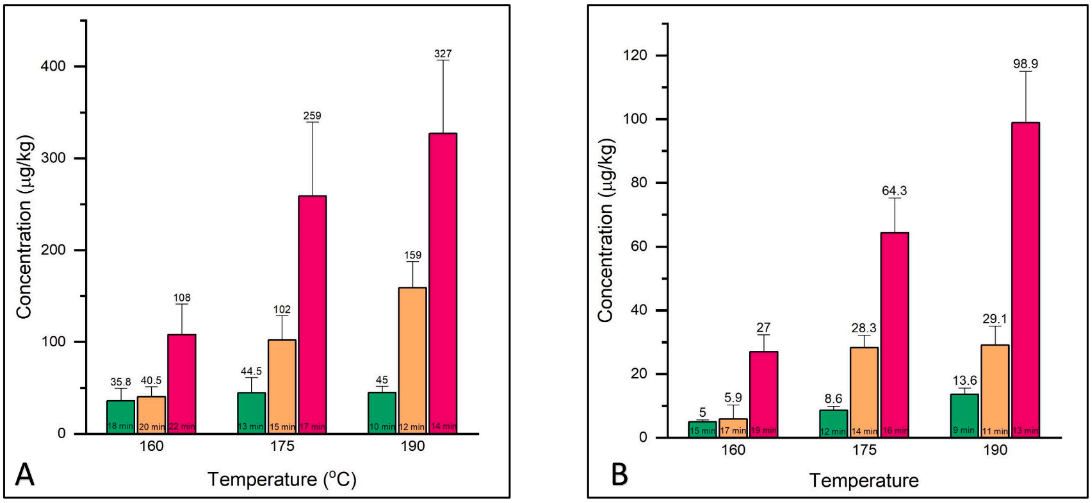

Fig. 2. Concentrations of acrylamide formed in sweet potato (A) and carrot fries (B) at different baking times and temperatures.

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, an observed linearity means the formation of acrylamide is exponential. The regression results are shown in Fig. 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 (>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 min, 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 (Fig. 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, $p =$

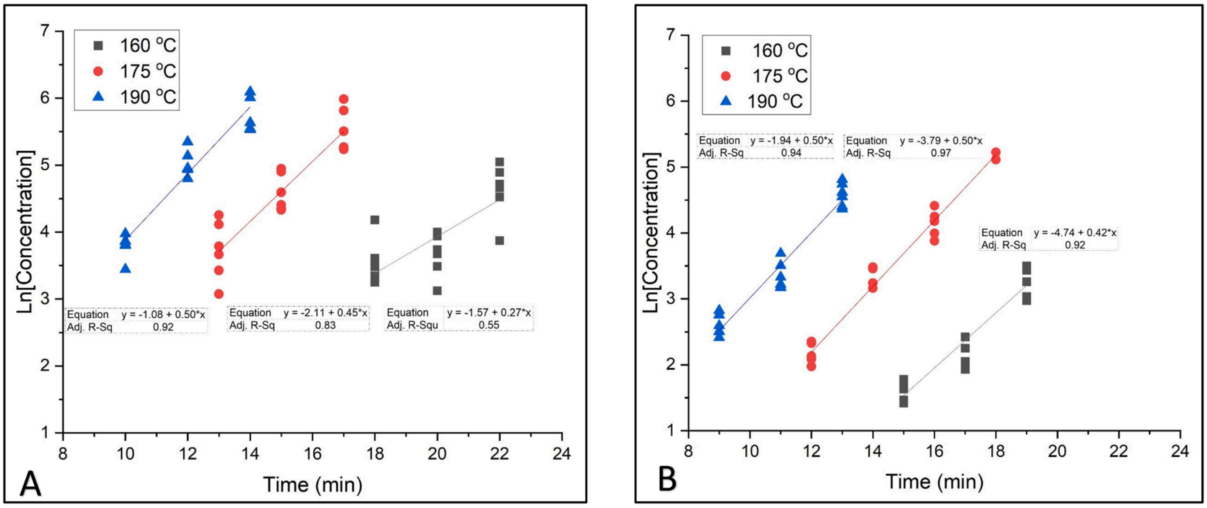

Fig. 3. Linear regression (95% confidence level) of natural log transformed acrylamide concentrations in sweet potato (A) and carrot fries (B) at different baking temperatures.

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 Fig. 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 (Fig. 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 10,000 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 10,000 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 min, 175 °C for 14 or 16 min, 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

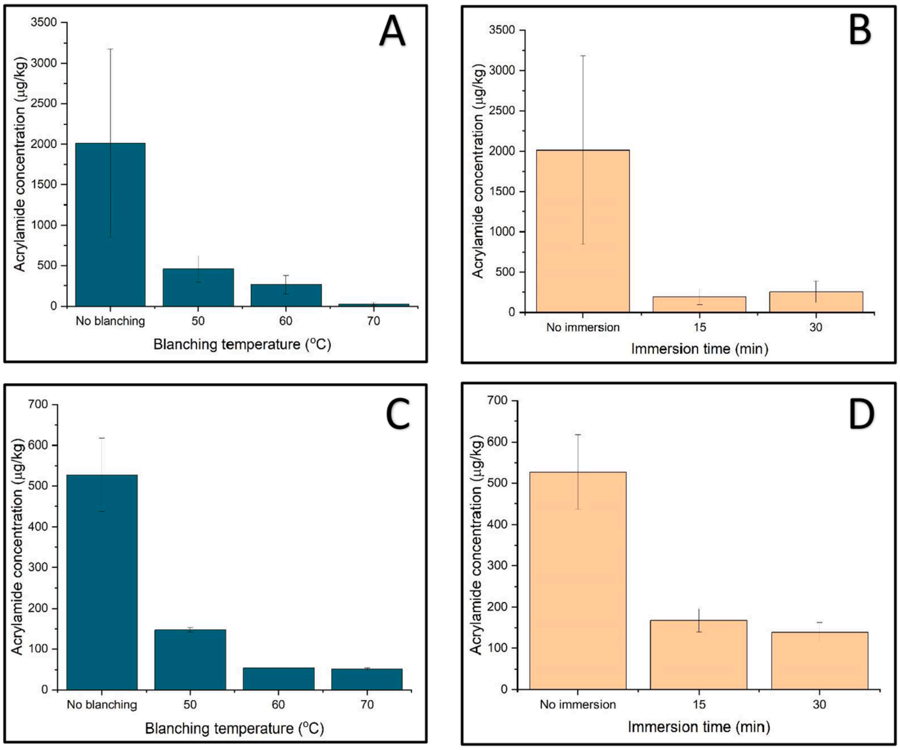

Fig. 4. Effects of blanching and immersion in acetic acid on acrylamide formation in oven baked sweet potato fries (A and B) and carrot fries (C and D).

Table 1
Margin of Exposure (MOEs) estimation for acrylamide; the table presents the MOEs for dietary exposure when consuming either carrot fries or sweet potato fries based on average concentration in both average and P95 exposure scenarios.

	Baking temperature (C)	Baking time (min)	Toddlers (1–3 years old)		Other children (3–10 years old)		Adolescents (10–18 years old)		Adults (18–65 years old)	
			Average	P95	Average	P95	Average	P95	Average	P95
Carrot fries	160	15	24,286	13,878	34,000	14,624	27,911	12,722	36,061	15,556
		17	20,582	11,761	28,814	12,393	23,653	10,781	30,560	13,183
		19	4498	2570	6297	2709	5169	2356	6678	2881
	175	12	14,120	8069	19,768	8503	16,228	7396	20,966	9044
		14	4276	2444	5986	2575	4914	2240	6349	2739
		16	1889	1080	2644	1138	2171	990	2805	1210
	190	09	8929	5103	12,500	5377	10,262	4677	13,258	5719
		11	4173	2385	5842	2513	4796	2186	6196	2673
		13	1228	702	1719	740	1412	644	1824	787
Sweet potato fries	160	18	3392	1939	4749	2043	3899	1777	5037	2173
		20	2999	1714	4198	1806	3446	1571	4452	1921
		22	1127	644	1577	679	1295	591	1673	722
	175	13	2349	1343	3289	1415	2700	1231	3488	1505
		15	1431	818	2003	862	1644	750	2124	917
		17	470	269	657	283	540	246	697	301
	190	10	2699	1542	3778	1625	3102	1414	4007	1729
		12	765	437	1070	461	879	401	1135	490
		14	381	218	533	229	438	200	565	244

P95: 95th percentile.

scenarios for carrot fries baked at 160 °C for either 15 min or 17 min.

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 10,000. Specifically, only carrot fries prepared at 175 °C for 16 min and 190 °C for 13 min showed concerning MoEs smaller than 10,000 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 min 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.

CRediT authorship contribution 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.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodchem.2022.132764.

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