FOODDRINK EUROPE

Acrylamide Toolbox 2026

Industry guidance for the mitigation of acrylamide formation in food



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Acronyms

AA	Acrylamide
ALARA	As low as reasonably achievable
Asn	Asparagine
Asp	Aspartate
CEN	European Committee for Standardization/Comité Européen de Normalisation https://www.cencenelec.eu/
EC	European Commission https://commission.europa.eu/index_en
EU	European Union
EFSA	European Food Safety Authority https://www.efsa.europa.eu/en
EUPPA	European Potato Processors' Association http://www.euppa.eu/en/
FBO	Food business operator
GAP	Good agricultural practice
GC-MS	Gas chromatography-mass spectrometry
GM/GMO	Genetically modified/Genetically modified organisms
GMP	Good manufacturing practice
Gln	Glutamine
Gly	Glycine
HACCP	Hazard analysis and critical control point
HPLC-MS/MS	High-performance liquid chromatography with tandem mass spectrometric detection
IARC	International Agency for Research on Cancer
JECFA	Joint FAO/WHO Expert Committee on Food Additives https://www.who.int/groups/joint-fao-who-expert-committee-on-food-additives-(jecfa)/about
LC-ESI-MS/MS	Liquid chromatography in combination with electrospray ionization and tandem mass spectrometry
LC-MS	Liquid chromatography-mass spectrometry
LC-MS/MS	Liquid chromatography-tandem mass spectrometry
MOE	Margin of exposure
MU	Measurement uncertainty
NON-GM	Non-genetically modified
PEF	Pulsed electric field
SME	Small and medium-sized enterprises
WHO	World Health Organization https://www.who.int/

Key changes to the Acrylamide Toolbox since 2019

- This toolbox update reflects both regulatory developments and current state of knowledge.
- Existing tools were assessed and categories were revised accordingly.
- New information on root vegetable-based snacks was added.
- Links were made with the multi-disciplinary research network ACRYRED (COST Action CA21149) to incorporate new findings targeting asparagine (Asn).
- An amidase which can be used for acrylamide (AA) reduction in soluble coffee and coffee surrogates was introduced.
- Non-genetically modified (non-GM) baker's yeast containing asparaginase enzyme, a new tool for AA reduction across various food and beverage applications, was introduced.

Summary

The FoodDrinkEurope Acrylamide Toolbox reflects the result of more than 20 years of cooperation between the food industry and national authorities of the European Union (EU) to investigate pathways of formation of AA and incorporate potential intervention steps to reduce exposure.

The aim of the toolbox is to provide national and local authorities, food business operators (FBOs), including small and medium-sized enterprises (SMEs), and other relevant bodies, with concise descriptions of intervention steps that may prevent or reduce the formation of AA in specific manufacturing processes and products. As such, the toolbox has been a useful aid for the correct implementation of Commission Regulation (EU) 2017/2158. In particular, it provides guidance for individual FBOs, including SMEs with limited research and development resources, to determine which of the intervention steps identified may be effective in reducing AA formation in their specific processes and products. Some of the tools and parameters are also expected to be useful in domestic food preparation and food service establishments, where strict control of cooking conditions may be more challenging.

The toolbox should be considered a "living catalogue" of tested concepts at different trial stages that will be updated with new findings that may be relevant for FBOs. New mitigation measures and strategies to reduce AA need to be readily available, cost-effective, and applicable at all scales of production across businesses of all sizes (especially medium, small, and micro businesses).

The ultimate goal is to select the most appropriate and practical solutions to reduce overall dietary exposure to AA. The latest version of the toolbox can be found at: https://www.fooddrinkeurope.eu/resource/acrylamide-toolbox/

On an international level, FoodDrinkEurope contributes to the Codex Alimentarius Commission review of the Code of Practice for the reduction of AA in foods (CXC 67-2009). This corroborates the global applicability and use of the toolbox approach across regions.

Finally, to support SMEs in implementing the toolbox, FoodDrinkEurope and the European Commission (EC) Directorate-General for Health and Food Safety collaborated with national authorities to develop AA brochures for six key sectors:

1. **Biscuits, Crackers & Crispbreads**
2. **Bread Products**
3. **Breakfast Cereals**
4. **Fried Potato Products (such as potato crisps)**
5. **Fried Potato Products (such as French fries)**
6. **Food for infants and young children**

FBOs can use the tools outlined in these brochures to adapt them to their specific production systems.

The brochures are available on the AA-dedicated site of the EC: https://food.ec.europa.eu/food-safety/chemical-safety/contaminants/catalogue/acrylamide_en



Background

In April 2002, authorities, the food industry, scientists, caterers and consumers were surprised by the discovery that many heated foods contained significant levels of AA, a substance previously known only as a highly reactive industrial chemical and present at low levels, for example, in tobacco smoke. It is now understood that AA is a common reaction product formed during a wide range of cooking processes and has likely been present in human diets since cooking began.

A wide range of cooked foods – whether prepared industrially, in catering, or at home – were found to contain AA at levels ranging from a few micrograms per kilogram (µg/kg) to levels exceeding 1000 µg/kg. These included staple foods such as bread, fried potatoes, and coffee, as well as specialty products like potato crisps, biscuits, crispbread, and other heat-processed foods.

At the time, toxicological data suggested that AA might be carcinogenic and pose a risk to humans. As a result, the European food and drink industry, working closely with the EC, national authorities, and the scientific community, invested significant resources in researching AA to better understand its formation pathways and to develop tools and techniques to mitigate its formation.

Assessments by the Joint FAO/WHO Expert Committee on Food Additives (JECFA), the Scientific Committee on Food, and the International Agency for Research on Cancer (IARC) confirmed that a risk from dietary AA intake could not be excluded, although relevance at typical dietary exposure levels, compared with other sources such as occupational exposure, was not established. The most recent JECFA evaluation in 2011 confirmed earlier findings, indicating a potential human health concern while also concluding that further data were needed to better estimate dietary risk. At EU level, research progress has been driven forward through stakeholder meetings, workshops and forums, and dedicated research networks, e.g., the latest COST Action on Reducing Acrylamide Exposure of Consumers by a Cereals Supply-chain Approach Targeting Asparagine.

Since 2002 several risk assessments of AA have been conducted. In 2015 the European Food Safety Authority (EFSA) Panel on Contaminants in the Food Chain concluded that, although human studies have not demonstrated that AA is a human carcinogen, the margin of exposure (MOE) based on current dietary intake levels across age groups indicates a concern for carcinogenic effects.

In 2022, EFSA reaffirmed that AA in food remains a health concern, as it is both genotoxic and carcinogenic, with potential to increase cancer risk across all age groups. EFSA concluded that new data did not warrant a full update of their 2015 assessment and continued to apply a MOE approach, and that due to its genotoxic potential, no safe level of dietary exposure, and therefore no tolerable daily intake could be established.

As no single solution exists to reduce AA across all affected foods, the food industry has taken collective responsibility to mitigate AA and has developed this guidance on techniques that are known to be reasonable in commercial settings.

The first FoodDrinkEurope Acrylamide Toolbox was published in 2005 with the support of EU and national authorities. Since then, it has represented the most comprehensive collection of knowledge on AA formation and mitigation across food categories. The present text is the 16th edition, incorporating the latest developments on AA mitigation and supporting FBOs in complying with Regulation (EU) 2017/2158, which is being reviewed as foreseen under Article 5.

This toolbox update reflects the evolution of the EU regulation and the state of knowledge.

Efforts by the food industry and academia are ongoing, as in most cases there are no easy (single) solutions due to the complexity of factors to be considered and the particularities of specific product categories. While research progresses (for example, to reduce natural precursors such as Asn in raw materials), any new mitigation measures introduced must be proven to be cost-effective and applicable at all production scales, particularly for SMEs.

This toolbox update reflects the evolution of the EU regulation and the state of knowledge.

Acrylamide formation

Most of the tools described in this document relate to what is now seen as the main formation mechanism of AA in foods, i.e. the reaction of reducing sugars with free asparagine (Asn) in the context of the Maillard reaction. In fact, not only sugars but also reactive carbonyl compounds may play a role in the decarboxylation of Asn – a necessary step in the generation of AA. More recently, quinones (e.g. caffeic acid quinone) have been shown to analogously react with Asn, resulting in AA formation.

Other theoretical pathways that do not require Asn as a reactant have been described in the literature, such as acrolein and acrylic acid. The thermolytic release of AA from gluten in wheat bread rolls was demonstrated as an alternative pathway. Based on molar yields, these mechanisms can be considered as only marginal contributors to the overall AA concentration in foods.

In many cooking processes, the Maillard cascade is the predominant chemical process determining colour, flavour and texture of cooked foods, based on highly complex reactions between amino acids and sugars, i.e. common nutrients present in all relevant foods. During cooking, the combination of temperature and heating time to which the product is subjected is pivotal for the formation of AA. In some product types it has been found that the AA content decreases during storage. This has been observed in packed roast coffees where it is based on a temperature-dependent reaction.

Asn and sugars are not only important and desirable nutrients, naturally present in many foods, but they are also important to plant growth and development. In most foods, they cannot be considered in isolation, since they are part of the highly complex chemical composition and metabolism of food plants. The Maillard reaction depends on the presence of a mixture of these common food components to provide the characteristic flavour, colour and texture of a given product. Thus, most of the Maillard reaction products are highly desirable, including some with beneficial nutritional properties and health effects.

Consequently, any intervention to reduce AA formation has to take due account of the highly complex nature of these foods, which therefore makes it very difficult to decouple AA formation from the main Maillard process.

It is essential to take into account that elimination of AA from foods is virtually impossible – the principal objective must be to try to reduce the amount formed in a given product. However, current knowledge indicates that for some product categories, what can be achieved is highly dependent on natural variations in raw materials. We also know now that the combination of mitigation methods in certain foods may unintentionally influence the formation of other process contaminants by shifting the Maillard reaction and lipid oxidation pathways. Thus, best practice in an industrial setting should be to monitor AA together with other process contaminants.

Whilst the toolbox focuses on industrial preparation of food, it can provide useful leads for domestic cooking and catering. Practical application at all food service levels would require additional efforts in consumer education and collaboration amongst stakeholders.



Definition and use of the toolbox

The summaries of AA reduction tools developed by industry are intended to be generic.

In light of the conclusions of the EFSA's risk assessments on AA in food, and the state of knowledge on AA, the food industry continues to reduce AA in food products to as low as reasonably achievable (ALARA) levels. However, the complete elimination of AA from food is not possible.

Moreover, significant variability may exist between product recipes, process and equipment design, and brand-specific characteristics, even within a single product category.

A total of fifteen tools have been identified, covering all production phases. Note that not all tools apply to every product type.

	**Agronomy**	• Reducing sugars • Asn
	**Recipe (Basic Formula, Ingredients, Product Form)**	• Raising/leavening agents • Other minor ingredients (e.g. Gly and divalent cations) • pH • Rework • Dilution/piece size • Fermentation • Non-GM baker's yeast containing asparaginase
	**Processing**	• Pre-treatment (e.g. washing, blanching, divalent cations) • Thermal input and moisture • Enzymes: asparaginase or amidase • Finished product colour • Texture/flavour
	**Final preparation**	• Consumer or end user guidance

The main food categories/sub-categories defined in the toolbox are as follows:

- Potato-based snacks
- Root vegetable-based snacks
- French fries and other cut (deep-fried) potato products
- Cereal/grain-based products (fine bakery wares and breakfast cereals)
- Fine bakery wares (biscuits, crackers, wafers, crispbread and gingerbread)
- Breakfast cereals
- Coffee
- Coffee substitutes (mainly based on cereals or chicory)
- Baby biscuits, infant cereals and baby foods other than cereal-based foods

It needs to be emphasised that **there is in most cases no single solution to reduce AA** in foods, even within a given product category. Indeed, individual processing lines dedicated to the manufacture of the same product in one factory may need different applications of the proposed tools. As an example, modification of thermal input for comparable product quality can be achieved by frying at a lower temperature for an extended time span, or by flash-frying for a very short time at higher temperatures. The choice will depend on the design and flexibility of the existing production equipment and desired final product design.

The summaries per category specify the level of experience available for a proposed intervention, i.e. trials conducted at (i) laboratory/bench, (ii) pilot, or (iii) industrial scale. Here, it is very important to discern interventions tested at laboratory or pilot scale and those that have been assessed in industrial trials.

- **Commercial application**: These interventions have been evaluated and implemented by some manufacturers in their factories. Application by other manufacturers may or may not be possible depending on their specific process conditions and desired final product design. The validation of the suggested tools was assessed over the product shelf life. The legal status of the proposed measures has been evaluated.
- **Development**: These concepts have been evaluated in pilot plants or factory test runs and have delivered measurable reductions to some extent, but have not yet been successfully applied under commercial production conditions. These tools may still have some risks to product attributes and/or inconsistent mitigation results. There may also be new applications of existing technologies, or tools at an agronomical level.
- **Research**: This indicates that – for the categories mentioned – only experimental work has been done to assess the impact of the proposed intervention. It is most likely that no quality tests (organoleptic, shelf-life studies, nutritional impact, etc.) have been conducted, nor full assessment of the legal status or possible intellectual property rights for the given intervention. Large-scale industrial application has either not yet been done or has failed in the specific context. This does not necessarily mean that the concept would not function for other applications.

Most of these tools have been evaluated only in an industrial, food processing context. Their usefulness for caterers or domestic cooking will need to be assessed separately, given the differences in cooking conditions and the typically lower level of standardisation and process control in non-industrial settings.

Where available, literature references are provided for the tool descriptions. In many cases, however, the summaries also include unpublished information provided by individual food manufacturers and sectors contributing to the joint industry program coordinated by FoodDrinkEurope.

The tools described do not comprise an exhaustive list of mitigation opportunities. The work of both industry and academic researchers continues and is likely to provide additional intervention leads or improvements. It is FoodDrinkEurope's intention to continuously update the toolbox to reflect such developments.

ALARA as applied to acrylamide

AA and other process contaminants are the result of naturally occurring chemical reactions in heated foods. Given that there are currently no levels that regulators have agreed upon as being safe, FBOs should make every reasonable effort (based upon current knowledge) to reduce levels in the final product, using the ALARA approach, thereby reducing consumers' exposure. ALARA could, for example, mean that an FBO changes parts of a process or even a whole process if technologically feasible.

The FoodDrinkEurope Toolbox explains the potential measures per food category to limit AA levels in the final product through interventions at various stages of production (agronomical, recipe, processing, and final preparation). They are based upon scientific knowledge and practical application in specific circumstances.

As technology develops, new tools for AA reduction may become available. FBOs should regularly review what tools are available and consider whether they can implement these tools into their processes or their product.

If an FBO chooses not to implement an available tool, then the responsibility should be placed upon the same FBO to demonstrate why its application is believed to be unreasonable or ineffective.

Considerations may include:

- Potential impact that the use of a known AA mitigation tool will have upon levels of AA in the final product
- Potential impact that the use of a known AA mitigation tool may have upon the formation of other process contaminants, e.g. furan, and/or reduction in control of other hazards, e.g. microbiological
- Feasibility of implementing the identified controls, e.g. legal compliance, commercial availability of the mitigation tool, occupational health hazards, timescales, and costs associated with upgrading or replacing plant equipment
- Impact that the use of a known AA mitigation tool will have on organoleptic properties and other quality aspects of the final product as well as product safety (the ideal method would have no adverse effects)
- Known nutritional benefits of using certain ingredients in preference to others, e.g. use of wholegrain cereals instead of refined cereals.

Methods of analysis and sampling

Today, many laboratories offer sensitive and reliable methods to analyse AA in a wide range of foods. Previous issues with the extractability of AA in certain food matrices were raised showing that a high extraction pH may significantly enhance the yield of AA versus extraction under neutral pH. Work done by independent research groups confirmed, however, that the apparently additional AA released at high pH is not due to the improved extractability of the analyte from the food matrix, but rather an extraction artefact formed due to the decomposition – under extreme pH conditions – of certain hitherto unidentified precursors. Consequently, the choice of reliable analytical methods is of major importance.

The main challenge for the analyst continues to be the high variability of the food products themselves. This starts from the natural variability of a given raw material. For example, any potato can be considered "individual" with noticeable differences in composition and thus potential for AA formation. Slight differences in product composition and process conditions, processing equipment capability, and even the temperature of the location where the production line is placed may lead to major differences in AA levels, often of several multiples between samples derived from the same product recipe made on the same production line.

Also, it should be noted that in the absence of a reliable rapid analytical methodology, it may not be practical for FBOs to use existing analytical methods as a positive release control. Analysis is therefore a measurement tool which is more typically to be used for establishing baselines for levels in a particular product/line and for monitoring or verification of the success (or otherwise) of the mitigation steps and controls in place within a factory and the supply chain.

Appropriate sampling and statistically relevant numbers of analyses are therefore essential to determine AA amounts in products, and to assess the actual reduction achieved by the mitigation step(s) when conducted in a factory setting.

No standardised sampling or analytical program has been defined within this document. In addition, the frequency of testing will depend on a wide number of factors including the variety of the raw material, seasonality, and country of origin; subsequently at the processing plant, by the different production lines, and process specifications.



Analysis and sampling requirements under EU law

FBOs within the EU should comply with the requirements on sampling and analysis as specified within Annex III of Commission Regulation (EU) 2017/2158, set out below. These can serve as reference.

I. Sampling

1. *The sample shall be representative for the sampled batch.*
2. *FBOs shall ensure that they undertake representative sampling and analysis of their products for the presence of acrylamide to verify the effectiveness of mitigation measures, i.e. the levels of acrylamide are consistently below the benchmark levels.*
3. *FBOs shall ensure that a representative sample of each product type is taken for analysis of acrylamide concentration. A 'product type' includes groups of products with the same or similar ingredients, recipe design, process design and/or process controls where these have a potential influence on acrylamide levels in the finished product. Monitoring programs shall prioritise product types that have the demonstrated potential to exceed the benchmark level and shall be risk-based where further mitigation measures are feasible.*

II. Analysis

1. *FBOs shall provide sufficient data to enable an assessment of the level of acrylamide and of the likelihood that the product type might exceed the benchmark level.*
2. *The sample shall be analysed in a laboratory that participates in appropriate proficiency testing schemes (which comply with the 'International Harmonised Protocol for the Proficiency Testing of (Chemical) Analytical Laboratories' (1) developed under the auspices of IUPAC/ISO/AOAC) and uses approved analytical methods for detection and quantification. Laboratories shall be able to demonstrate that they have internal quality control procedures in place. Examples of these are the 'ISO/AOAC/IUPAC Guidelines on Internal Quality Control in Analytical Chemistry Laboratories'.*

Wherever possible the trueness of analysis shall be estimated by including suitable certified reference materials in the analysis.

3. *The method of analysis used for the analysis of acrylamide must comply with the following performance criteria:*

Parameter	Criterion
Applicability	Foods specified in this Regulation
Specificity	Free from matrix or spectral interferences
Field blanks	Less than limit of detection
Repeatability (RSD_r)	0.66 times RSD_R as derived from (modified) Horwitz equation
Reproducibility (RSD_R)	As derived from (modified) Horwitz equation
Recovery	75–110%
Limit of detection	Three tenths of limit of quantification
Limit of quantification (LOQ)	For benchmark level < 125 µg/kg: ≤ two fifths of the benchmark level (however not required to be lower than 20 µg/kg) For benchmark level ≥ 125 µg/kg: ≤ 50 µg/kg

4. *Analysis of acrylamide can be replaced by measurement of product attributes (e.g. colour) or process parameters provided that a statistical correlation can be demonstrated between the product attributes or process parameters and the acrylamide level.*

III. Frequency

1. *FBOs shall undertake sampling and analysis at least annually for products that have a known and well-controlled acrylamide level. FBOs shall carry out higher frequency sampling and analysis of products having the potential to exceed the benchmark level and shall be risk-based where further mitigation measures are feasible.*
2. *Based on this assessment referred to in point II.1, the FBOs shall specify appropriate frequencies for analysis for each product type. The assessment shall be repeated if a product or process is modified in a way that could lead to a change in the acrylamide level in the final product.*

European Committee for Standardization (CEN)

EN standard 16618:2015 Food analysis – Determination of acrylamide in food by liquid chromatography in combination with electrospray ionization and tandem mass spectrometry (LC-ESI-MS/MS)

FBOs should also be aware that the CEN has published a method for the determination of AA in bakery ware such as bread; toasted bread; crispbread; butter cookies; and biscuits; potato products such as potato fries, potato crisps, and potato pancake; and roasted coffee by LC-ESI-MS/MS. This method has been validated in an interlaboratory study via the analysis of both naturally contaminated and spiked samples, ranging from 14.3 µg/kg to 9,083 µg/kg.

Other relevant EN standards and Technical Specifications include:

- EN ISO 18862:2026 – Coffee and coffee products – Determination of acrylamide – Methods using high-performance liquid chromatography with tandem mass spectrometric detection (HPLC-MS/MS) and gas chromatography-mass spectrometric detection (GC-MS) after derivatization (ISO 18862:2025)

(Note: This standard replaced EN ISO 18862:2019 – Coffee and coffee products – Determination of acrylamide – Methods using HPLC-MS/MS and GC-MS after derivatization (ISO 18862:2016)

There is also a CEN Technical Specification (CEN/TS 17083:2017) which specifies a method for the determination of AA in cereal-based products, potato-based products and coffee by GC-MS. The method has been single-laboratory validated via the analysis of spiked samples (French fries (uncooked), bread, water biscuit, infant cereal, biscuit, green coffee, roast coffee and instant coffee), ranging from 30 µg/kg to 1500 µg/kg AA.

Moreover, it is recommended to verify the minimum sampling and performance requirements of both Commission Regulation (EU) 2017/2158 and Commission Implementing Regulation (EU) 2024/1045.

In parallel, method standardization efforts are ongoing at AOAC International. A liquid chromatography tandem mass spectrometry (LC-MS/MS) method for AA determination in food was evaluated and approved as official first action by the AOAC Expert Review Panel in late 2023, following the conclusion of its successful validation (AOAC Official First Action 2023.01).

This method allows for analysis of low levels of AA in a broad range of food commodities (coffee, cereals, baby food, cocoa, dry pet food, potato products, vegetable crisps, biscuits, tea, nuts, and spices).

Analytical reliability

While the 2009 EFSA report on the *Results on the monitoring of acrylamide levels in food* (EFSA Scientific Report (2009) 285: 11) accurately highlighted high measurement uncertainty (MU) and variable detection limits for AA in that era, these findings are no longer representative due to the stricter EU regulatory standards and advancements in mass spectrometry, specifically the shift to tandem mass spectrometry. In recent years, there has been a significant update within laboratories regarding analytical performance and MU for AA. EFSA data collections and Joint Research Centre (JRC) proficiency tests demonstrate that the analytical landscape for AA has become highly standardised. The vast majority of data sent to EFSA now relies on LC-MS/MS or GC-MS/MS using stable-isotope-dilution assays.

Generally speaking, the vast majority of modern, accredited laboratories can analyse AA highly reliably. While it was a major technical obstacle in the 2000s, specialised food testing laboratories have mastered this analysis. However, a further potential confounding factor for FBOs, on top of the natural variability within product, will be laboratory to laboratory and country to country comparability, irrespective of the analytical method used.

It is best practice to check accreditation to ISO/IEC 17025:2017 and validated methods of analysis before choosing to work with a laboratory.



Further considerations for regulatory compliance

FBOs must also evaluate any intervention for its wider regulatory impact. For example, for many products, the use of additives is strictly regulated and changes in recipes will not only affect the ingredient list but potentially also the product name, description, and customs classification. Additionally, process conditions and equipment standards must continue to meet relevant official standards. New potential ingredients or processing aids need to undergo regulatory approval, including any health and safety considerations. For new plant cultivars, success in breeding must be followed by formal approval of the new seed. All these considerations can influence the choice of interventions and the time for implementation/commercialisation.

Advances in food science have led to the development of specialised, food-grade enzymes (or yeast products containing enzyme activity), including those used to reduce AA levels in food products.

The use of food enzymes in the industry is well established but regulatory permission to apply enzymes in foods still requires clarification, nationally and internationally.

In the case of enzymes used for the reduction of AA such as asparaginase or amidase, their production needs to be conducted under certain food hygiene principles, and the product needs to be approved as food enzymes in the jurisdiction of intended use. For example, companies are today producing commercial food-grade enzyme preparations or non-GM baker's yeast with enzyme activity, many of which have received positive safety evaluations from EFSA. As global patent holders, companies producing commercial food-grade enzymes may sub-license the rights to FBOs to incorporate such enzymes in their food production processes.

Enzyme permissibility

In 2008, the EC adopted Regulation (EC) No. 1332/2008 to harmonise provisions on the use of enzymes in food across the EU. According to this regulation, all food enzymes must undergo a safety evaluation by EFSA, and approval is granted through their inclusion in the Union list of food enzymes established by the EC.

The Union list is still under development. Numerous applications have been submitted and are currently under EFSA review. Until the list is finalised, the marketing and use of food enzymes – and of foods produced with them – remain subject to the national legislation of each Member State.

Outside the EU, regulatory frameworks vary considerably. Some countries have no specific rules on enzymes, while others regulate both their use in production and the marketing of foods produced with them.

Enzyme labelling

Under Regulation (EC) No 1332/2008, food enzymes are generally considered processing aids if they no longer perform a technological function in the final product. In such cases, they are not required to appear on the ingredient list of food labels in the EU, in accordance with Article 20(b)(ii) of Regulation (EU) No 1169/2011.

Regulatory authorisation

FBOs should carefully ensure that all regulatory requirements and authorisations, including potential impact on product properties, are fulfilled in both the country of production and the target market.

Risk/risk and risk/benefit

Mitigation of AA formation through changes in product composition and/or process conditions may have an impact on the nutritional and taste qualities (e.g. decreased nutrient bioavailability; changed flavour, taste/palatability, texture), and safety of food (e.g. inadequate reduction of microbial load, inadequate decomposition of natural toxins or inadvertent formation of other undesirable substances). There may also be potential loss of beneficial compounds generated during cooking which are known to have protective health effects, e.g. antioxidants and in vitro antioxidant capacity of heated foods. Additional considerations are as follows:

- Frying potatoes at lower temperatures to achieve a comparable texture can reduce AA formation but requires longer cooking times and may consequently increase fat uptake.
- Excessive blanching of potatoes results in further loss of minerals and vitamins.
- Using refined flour reduces AA formation potential but is seen as less nutritionally desirable compared with wholegrain (bran) products.
- Replacing ammonium bicarbonate with sodium bicarbonate can reduce AA formation but may increase sodium levels and conflict with sodium-reduction efforts. A risk-benefit analysis found that the resulting increase in sodium intake was small: only 1.3% of the population exceeded 40 mg/kg body weight/day, and intake remained well below EFSA's proposed acceptable daily intake of 2 g/day.
- Any mitigation measure needs to carefully assess the potential of formation of other undesirable process contaminants.

Therefore, for any proposed intervention, a risk vs risk or risk vs benefit evaluation should be conducted.

The risk vs risk evaluation should be aimed at avoiding the creation of a potentially larger risk upon the reduction of another, e.g. unintentional formation of other process contaminants upon application of mitigation measures for the reduction of AA.

In terms of risk vs benefit evaluation, as an example, a thorough assessment of the benefits and risks of consumption of wholegrain cereals was published in 2022 by the Swedish Food Agency (Livsmedelsverket). The 2022 report showed that a significant reduction in coronary heart disease outweighed the risks of higher cadmium dietary exposure in the adult population via consumption of wholegrain foods. A comparative exercise positioning the possible risk of AA dietary exposure versus the consumption of wholegrain products has, unfortunately, not been considered yet.

It is important that FBOs carefully assess the suitability of proposed mitigation steps in the light of the actual composition of their products, their manufacturing equipment, and their need to continue to provide consumers with quality products consistent with their brand image and consumer expectations.

It should be noted that measures aimed at reducing levels of AA cannot be chosen in isolation from other parameters of food quality and safety. Precautions need to be taken to avoid compromising the existing chemical and microbiological safety of the food. The nutritional qualities of products also need to remain unimpaired, together with their organoleptic properties and associated consumer acceptability. This means all mitigation strategies need to be assessed with regards to their benefits and any possible adverse effects.

For example:

Checklist for choosing and evaluating mitigation measures

- When considering AA mitigation measures, ensure they do not increase other process contaminants, such as aldehydes, hydroxymethylfurfural, N-nitrosamines, polycyclic aromatic hydrocarbons, chloropropanols, ethyl carbamate, furan, heterocyclic aromatic amines, or amino acid pyrolysates.
- AA mitigation measures must not compromise the microbiological safety or stability of the final product. Particular attention should be paid to final product moisture content and, for jarred baby foods, to the effectiveness of heat treatment in reducing microbial loads to acceptable levels.
- AA mitigation may adversely affect the organoleptic properties of the final product. As AA formation is closely linked to the colour, flavour and aroma of cooked foods, any changes to processing conditions, raw materials or ingredients should be assessed for consumer acceptability.
- AA mitigation measures must not compromise the nutritional quality of the product.
- Potential new additives, enzymes and processing aids may require formal safety assessments, efficacy demonstrations and regulatory approval.
- AA levels can vary considerably, even within the same production batch or between production sites using identical processes, ingredients and formulations.
- Manufacturers should be aware that variability in raw materials and poorly controlled heating equipment can complicate mitigation trials and may mask changes in AA levels.

Manufacturer's playbook

- **Manufacturer-specific considerations:** Each manufacturer must evaluate how a mitigation measure can be implemented under its own production conditions. Measures that are effective in laboratory or pilot-scale trials may not deliver the same results in commercial production.
- **Interactions between mitigation measures:** Multiple mitigation measures are often applied simultaneously. Their combined effect may be less than the sum of the individual interventions. In products with complex formulations, such as biscuits, the actual impact of a given measure can be difficult to predict**.**
- **Process compatibility:** Any proposed mitigation measure should be assessed for its practicality and integration into existing manufacturing operations. Considerations include available space for additional equipment or ingredients, impacts on line speed and productivity, and compatibility with existing equipment, including potential corrosion from food-grade acids.
- **Natural variability:** Foods are derived from natural raw materials such as cereals, potatoes and coffee beans. Their composition varies according to cultivar, harvest season, climate, soil conditions and agricultural practices, and can also change during storage and processing. These factors are not yet fully understood or consistently controlled, and their effect on AA formation may exceed that of the mitigation measures themselves.
- **Process variability:** AA levels can vary considerably within a product range and even between batches of the same product. To reliably assess the effect of a mitigation measure – particularly when several changes are introduced at once – a statistically significant number of analyses under steady-state conditions is required. Single analyses are rarely sufficient.
- **Brand-specific consumer acceptance:** Manufacturers should assess the impact of mitigation measures on the characteristics that define their products and brands. Although a modified product may remain acceptable in general, it may no longer meet consumer expectations for an established brand. As a result, reducing AA in existing products may be more challenging than in newly developed products.

Potato-based snacks

Snacks made from potatoes *(Solanum tuberosum)* sliced and fried; or fabricated products made from potato-based ingredients (flakes, granules, etc.)



Agronomy: Reducing sugars

General considerations

Due to an abundance of free Asn in potatoes, reducing sugars are seen as the key limiting factor for the formation of AA in potato-based snacks. In the context of potato-based products, the key reducing sugars are fructose and glucose. The reducing sugar content of the tuber correlates well with the AA concentration in the final product, especially if the fructose:Asn ratio is <2.

Commercial application

- Minimising reducing sugars is part of standard manufacturing practices in the industry
- Control of tuber storage temperature identified as good practice
- Use of sprout suppressants, where legally permitted, to prevent sweetening during storage

Controlling reducing sugars is currently the primary measure employed by the industry to reduce AA levels in potato-based snacks. This is achieved through:

- Selection of potato varieties with reducing sugar concentrations that are suitable for the product type
- Minimising the risk of high reducing sugars by growing those low-sugar varieties best suited to the local growing conditions, by appropriate field selection, and by adherence to agronomy best practice
- Ensuring tubers are mature at time of harvesting (immature tubers tend to have higher reducing sugar levels)
- Selecting lots based on reducing sugars content (reducing sugar levels should be monitored throughout storage)
- Controlling storage conditions from farm to factory, e.g. managing temperature (at least above 6°C for long-term storage, but temperature specified for the individual potato variety stored) and humidity to minimise senescent sweetening
- Reduction of tuber sprouting with permitted sprout suppressants or techniques and following good agricultural practice (GAP)
- For potatoes stored at lower temperatures, reconditioning at higher temperature (e.g. ambient) over a period of a few weeks
- Adequate scheduling processes are recommended for the transition out of storage to ensure a timely use of potato loads at the factory
- Selecting potato-based raw materials (flakes or granules) with the lowest possible reducing sugar level to deliver the appropriate product attributes

[Note: Potato flakes are not typically produced from specific potato varieties and therefore have the potential to be a highly variable ingredient; however, there are a number of mitigation tools available to reduce levels of reducing sugars. Commission Regulation (EU) 2017/2158 requires that for each product, FBOs shall specify target values for reducing sugars in their dehydrated potato ingredients, and that the target value of reducing sugars in the products concerned shall be set as low as feasibly possible, taking into account all relevant factors in the design and production of the finished product such as the amount of potato ingredients in the product recipe, further possible mitigation measures, further processing of the dough, seasonality, and the moisture content in the finished product. Where the content of reducing sugars is higher than 1.5%, the FBOs shall provide data demonstrating that level of AA in the finished product is as low as reasonably achievable and that the benchmark level is achieved.

Additionally, some manufacturers have reported that for some specific potato varieties it is necessary to store potatoes at temperatures at >8°C, and that with good storage controls it is possible to keep them in good condition for longer periods of time without relying on higher amounts of sprout suppressant treatments.]

Future considerations

- Breeding new potato varieties with lower reducing sugar content and/or less susceptibility to cold-induced sweetening
- Further optimise agricultural practices to minimise reducing sugars and free Asn

Agronomy: Asparagine

Development

Selection of crop varieties based on typical free Asn:total free amino acids ratio

Research suggests that the impact of farming practices (e.g. fertiliser regimes) may have an effect on amino acid ratios in potatoes. Nitrogen and sulphur fertilisation may alter the ratio of free Asn:total free amino acids in a tuber, and research has suggested that this ratio (and in particular, the Asn:glutamine (Gln) ratio) is potentially of greater significance to the formation of AA in potatoes than previously thought.

However, the effects of fertilisation are variety-specific, and so far, no optimum amino acid ratio in potato has been established.

Research

Control of Asn levels in tubers

Farming practices, e.g. fertiliser regimes

Laboratory and field studies with new potato varieties

Asn, an important amino acid for plant growth, is the other key reactant for AA formation. In potatoes, Asn is the most abundant free amino acid, typically 0.2–4% dry weight, and 20–60% of total free amino acids. Asn levels do not correlate to reducing sugar levels.

Also, on its own, the reducing sugar concentration of potatoes is not always directly proportional to the AA concentration observed in a potato product. The concentration of free Asn and the ratio of free Asn to other free amino acids (of which Gln is by far the most abundant) contribute to the variance in AA-forming potential, and should also be considered as indicators of the relative AA risk of different potato varieties. Varieties with a lower ratio of Asn to other free amino acids would be expected to have lower AA risk (for a given reducing sugar content).

So far, no control of Asn levels in potatoes has been established. Potential leads being explored include:

- Breeding of lower Asn varieties
- Impact of storage on free Asn levels
- Impact of farming practices (e.g. fertiliser regimes) on Asn:total amino acids levels

Generally, increased nitrogen fertilisation raises the AA-forming potential of potatoes, and nitrogen fertilisation should be kept at the minimum level to ensure the health and yield of the crop. Sulphur fertilisation may mitigate the effect of high levels of nitrogen fertilisation. However, the effects of fertilisation levels are highly variety-specific, and no general advice has been issued.

In field trials in the USA, new potato varieties with reduced expression of an Asn synthetase gene in the tuber have reduced amounts of free Asn up to five-fold. Heat-processed products derived from such tubers show comparable sensorial properties to their conventional counterparts, and much lower levels of AA (50–75% reduction). These varieties are available for commercial cultivation in markets outside the EU but are considered to be genetically modified organisms (GMOs).

At the time of writing, such potatoes are not yet approved for commercial production within the EU; therefore, the regulatory status should be checked.

General considerations

- Minimising reducing sugar content needs to be balanced against processing methods and final product characteristics (colour, flavour, etc.).
- Elimination of materials outside specification as part of standard good manufacturing practice (GMP) has proven to be an effective measure to reduce AA in the final product. This can be done through working with suppliers to ensure that incoming potatoes are checked whilst in storage, and again at plant, for defects (e.g. bruising and damage, viruses such as Spraing/tobacco rattle virus (TRV), fungal diseases, storage rots).

Recipe: Other minor ingredients (amino acids, calcium salts and co-ingredients)

Commercial application

▶ Certain minor or co-ingredients have the potential to contain comparatively high levels of AA, which can impact levels in the final product

Dough-based potato crisps, snacks and crackers

Co-ingredients

Techniques associated with the production of some minor ingredients could result in high levels of AA in those ingredients, e.g. pre-processed cereals, processed sugars such as molasses, or certain processed spices/flavourings used in the dough. These could potentially raise overall AA levels in the final product.

There may be an impact with co-ingredients included in a composite product (e.g. pre-processed cereal pieces, vegetables, nuts, seeds) where they could be “cooked” several times over. This needs to be deliberately taken into account in product design, processing practices, and issues with processing equipment and performance.

Development

- In some wet dough-based systems, it may be possible to use the following substances, taking into account the requirements of the specific end product, and its production methods:
  - Amino acids
  - Calcium salts

Dough-based potato crisps, snacks and crackers

Amino acids

- Other amino acids may compete with Asn and can thereby reduce AA formation; alternatively, they may chemically react with AA, e.g. through Michael addition. Shifting the balance away from Asn may help to reduce AA formation.
- In some wet dough-based potato snacks, the addition of amino acids at levels showing a reduction in AA can produce unacceptably high levels of browning and bitter off-flavours.
- At lower levels, amino acid use may have an AA-reducing effect while still maintaining acceptable colour impact.

Calcium salts

- Treatment of potato flakes with calcium salts during their production or addition of calcium salts in the dough recipe have demonstrated up to 30–40% AA reduction dependent on the product design and formulation.
- Excessive levels of calcium salts can, however, generate undesirable product attributes.
- Precautions should be taken to ensure that other process contaminants (e.g. chloropropanols, 3-MCPD) are not formed as a result of this mitigation.

Recipe: pH

Commercial application

- Addition of acids: the use of acids and their salts has been proven effective at commercial scale in some products

Dough-based potato crisps, snacks and crackers

Addition of acids and their salts

The addition of citric, lactic or ascorbic acid has been found to successfully reduce AA and is used commercially for some types of wet dough-based potato crisps, snacks and crackers.

However, the addition of acids to some products produced strong off-flavours. This taste impact was not observed in other cases, indicating that potential for success varies considerably depending on product design.

Studies so far show that the effect of acids is dependent on product design and can lead to quality issues unless carefully controlled.

Research

- Combined treatment of acid and Gly can be applied to balance flavour formation

Acidulants in combination with glycine (Gly)

In a potato cake model, the combined treatment of citric acid and Gly (each 0.39% in the recipe) had an additive effect in reducing the AA concentration. Citric acid inhibits certain flavour formations, compensated by the addition of Gly which favours the formation of certain volatiles.

Recipe: Dilution and piece size

Commercial application

- Partial replacement with ingredients lower in key reactants can be effective

Dough-based potato crisps, snacks and crackers

For some dough-based potato crisps, snacks and crackers, partial replacement of potato components by ingredients lower in key reactants can reduce AA formation potential, e.g. use of ingredients containing lower concentrations of AA precursors. (Note: the possibility to amend recipes through substitution is limited by the impact upon the characteristics of the products (e.g. expansion rates, texture, flavour) and finished product labelling (e.g. standards of identity of some products).

- Thicker-cut potato crisps may have higher AA due to increased temperature or fry time required to reach final moisture levels

Sliced potato crisps

Sliced potato crisp products are fried to a fixed low moisture content. Theoretically, thicker sliced potato crisps may have a higher AA forming potential as they will require a higher temperature and/or longer fry time to reach the same moisture end point as a thinner sliced potato crisp product.

Slice thickness is, however, an important product characteristic for sliced potato crisps and is difficult to address without fundamentally altering the finished product.

Recipe: Fermentation

Development

- Lower levels of AA can be achieved by fermentation

Dough-based potato crisps, snacks and crackers

Fermentation reduces levels of key reactants for the formation of AA and lowers the pH.

The use of Lactobacillus to treat potatoes has been proposed. Whilst work is ongoing, this option is currently not suitable for use in the context of most current processes and available equipment, and will potentially create off tastes and reduce product stability.

General considerations

There may not always be a synergistic effect derived from use of multiple recipe mitigation steps, e.g. specifically applying to asparaginase (see below) and lowering pH.

AA formation in potato-based foods is driven primarily by thermally induced, non-enzymatic browning reactions, with the Maillard reaction representing the dominant pathway. However, a proportion of AA is likely to arise from an acrolein pathway. The potential for AA from the acrolein pathway will vary according to the frying conditions, including oil type, temperature, duration, water activity, and oil oxidation status. Shorter frying times, fresh or stabilised oil conditions, and higher moisture will all limit acrolein availability, however its contribution will always remain minor relative to the dominant Maillard pathway.

Processing: Asparaginase

Commercial application

- Asparaginase may reduce AA in reconstituted dough-based products, but off-flavours can be created in some recipes

Dough-based potato crisps, snacks and crackers

Asparaginase can significantly reduce the levels of AA in fabricated potato-based products. At a commercial scale, the enzyme's effectiveness is recipe-and process-dependent and requires a delicate balance of reaction conditions (e.g. pH, water activity, ingredient and enzyme dosing) and contact time to be effective. FBOs shall follow enzyme manufacturer recommendations for proper storage and handling, especially during the summer months.

In some recipes, the excess Asn in potatoes may result in the by-products aspartate (Asp) and ammonia that can be formed in sufficient quantities to impart off-flavours.

Research

- Asparaginase may reduce AA in an optimised laboratory environment; however, this differs significantly from an industrial setting

Sliced potato crisps

Treatment of fresh slices of potato with asparaginase has been found to be ineffective in pilot and industrial settings. This is because the enzyme cannot penetrate the potato slice/cell walls sufficiently to act upon the Asn. Extended soak/pre-treatment of such thin slices of potato with asparaginase results in disintegration of the slice structure.



Processing: Thermal input and moisture

General considerations

Moisture content has a strong influence on the kinetics of both browning and AA formation. Studies have shown that, at low moisture contents, AA formation can become more sensitive to temperature than browning reactions. Consequently, the final stage of frying is particularly important and should be carefully controlled to optimise colour development while minimising AA formation.

Commercial application

- Thermal input controls AA formation in the finished product
- Controlling moisture helps to manage cooking control

Sliced and dough-based potato crisps, snacks and crackers

Thermal input rather than temperature alone is critical to controlling product characteristics. This needs to take account of temperature and frying times and processing equipment.

Different solutions to optimise thermal input to manage AA have been implemented in line with existing processing equipment.

- Vacuum frying offers an alternate thermal input control system; however, this technology is not widely available and has limited throughput capacity. Vacuum frying may not deliver desired product attributes given the lack of Maillard compounds formed. Additionally, vacuum frying leads to much harder products and significantly changes the product characteristics.
- For manufacturers that use high temperature flash-frying, rapid cooling helps to reduce AA formation.
- Moisture in the fried product is critical for successful industrial implementation of cooking control. Therefore, it is important to fry to the maximum end moisture content that makes an acceptable product.
- The target moisture level should be set as high as feasibly possible on a specific line and for a specific product, in line with expected quality and food safety standards, and taking into account relevant factors.
- The absolute minimum moisture content for sliced and dough-based potato crisps, snacks and crackers should not be lower than 1.0%.
- The baking/drying/frying exit temperature should be as low as feasibly possible on a specific line and for the specific product, in line with expected quality and food safety standards, and taking into account relevant factors.
- For sliced potato crisps, typically the fryer exit temperature should not be higher than 168°C, whereas for dough-based potato crisps, snacks and crackers – where there are a greater variety of production methods, recipes and available mitigation measures – typically the temperature at the end of the baking/drying/frying process should not be higher than 175°C.

Specific temperature/dwell time guidance is product design-, composition- and process-dependent. The control of total thermal input considering dwell time and temperature to achieve a specific finished product moisture is fundamental to slowing down the Maillard reaction and AA formation reaction rates.

Other considerations

FBOs should consider the effect of reducing the frying temperature on the fat content of the finished product (i.e. dropping the outlet frying temperature by about 5°C from design may lead to an increase in fat uptake when frying to the same moisture endpoint).

Although higher moisture levels may be an effective tool to reduce AA formation, FBOs should also consider the subsequent impact this may have on product quality, shelf life, and/or microbiological damage.

FBOs should consider the effect of incomplete cooking on moisture levels in products and its subsequent impacts on the same.

[Note: Most pellet products are fried at temperatures higher than 175°C because of their very short frying time and the temperatures needed to achieve the required expansion and texture of these products. Furthermore, programs to reduce sodium in pellet products can have unintended consequences with regards to the need to fry at higher temperatures to achieve the same expansion and texture.]

Processing: Pre-treatment (e.g. washing, blanching, divalent cations)

Commercial application

Blanching of potato sticks prior to processing

Sliced potato crisps (potato stick products only)

Blanching of potato stick-type products (sliced from whole potatoes) to reduce levels of reducing sugars has been proven to reduce AA levels, in some product designs, without the same degree of negative side-effects on flavour, texture and oil content uptake as seen with standard sliced potato crisps.

[Note: Some manufacturers report that, in some product designs, blanching does still have an impact upon texture.]

Use of PEF technology

Sliced potato crisps

In recent years, snacks machinery manufacturers have introduced patented pulsed electric field (PEF) technology.

The PEF process works by perforating the cell walls of a potato slice, creating micro-holes that allow Asn and reducing sugars to be washed out of the potato in a cold wash. PEF treatments result in more uniform frying and lower surface sugar concentration by enhancing electroporation, thus decreasing AA formation.

Whilst this technology has not proven to be effective in all applications, some companies have succeeded in using PEF as an alternative to blanching where the tubers are of a lower quality (e.g. higher reducing sugars content).

[Note: Significant capital investment, research and training are necessary to use PEF technology to its full potential.]

Development

- Peeling and washing of potatoes prior to processing
- Blanching of potato slabs prior to flake/granule production and blanching of potato slices

Sliced and dough-based potato crisps, snacks and crackers

It has been reported that in some potato varieties, reducing sugars have been found at higher levels in the peel layer, and that peeling can help in overall reduction in these cases. However, the impact of peeling on overall AA levels is highly dependent on the potato variety and season.

Blanching may be an option in the production of potato flour, flakes or granules.

However, blanching of sliced potato crisps is not desired as it results in loss of flavour, loss of texture, and increased oil content of the finished product due to the disruption to the potato cells on the surface of the slices and therefore is not a preferred mitigation tool.

- The addition of di-and trivalent cations proposed to reduce the formation of AA

Calcium salts

The addition of di-and trivalent cations in pretreatments has been proposed to reduce the formation of AA in several potato products.

- Laboratory research using calcium salts found AA reduction in potato crisps not attributable to a lower pH. Sensory tests from laboratory scale claimed good acceptability, but industry experience with calcium use suggests bitter off-flavours and brittle textures – this requires confirmation with products fried to same moisture content.
- The use of magnesium chloride gave rise to serious off-tastes.
- Increase in content of other process contaminants might result from the use of calcium or magnesium chloride in certain foods. Appropriate testing should be conducted.

Research

- The use of an AA reducing yeast proposed to reduce the availability of Asn prior to and/or during processing

Dough-based potato crisps, snacks and crackers

Laboratory scale research using a patented, non-GM, asparaginase-expressing baker's yeast strain ARY-2 (Saccharomyces cerevisiae) have reported acrylamide (AA) reductions of up to 83% in potato-based snacks, but the technology has yet to be scaled up to commercial production in this food category. The yeast has reported GRAS status in the USA and has received a positive EFSA safety evaluation, which does not constitute EU authorisation while the Union list of food enzymes remains pending.

The yeast works by breaking down Asn in the raw ingredients into Asp and ammonia (nitrogen). Like asparaginase treatments, the tool requires sufficient contact time to be effective, and the yeast's efficacy will be dependent on the recipe and process.

[Note: For sliced potato crisps, the yeast cannot penetrate the potato slice/cell walls sufficiently to act upon the Asn.]

Extended soak/pre-treatment of such thin slices of potato with yeast could result in disintegration of the slice structure (as with asparaginase).

Processing: Finished product colour

Commercial application

- In-line colour (optoelectronic or manual) sorting can be an effective measure to remove darker products which may in turn have a higher AA level
- Finished product colour

Sliced and dough-based potato crisps, snacks and crackers

Elimination of darker-coloured products by in-line colour sorting (optoelectronic or manual) has proven to be an effective measure to reduce AA.

Darker-coloured products are more likely to have come from individual potato tubers that are higher in reducing sugars, and these could potentially increase the AA level in a given sample by up to 25–50%, with the magnitude of impact depending on sample size, product heterogeneity, and the proportion of darker crisps in the sample.

There is evidence to suggest that consumers dislike very pale products; however, lighter-coloured products could be acceptable for a consumer if other organoleptic properties such as taste and texture are managed. For example, use of ingredients such as paprika to add colour post-frying may compensate for lighter-coloured potato crisps.

[Note: It may not always be technically feasible to use in-line optoelectronic sorting for potato stick-type products, depending on product geometry, presentation to the sorter, sorter capacity, and equipment capability. Appropriate product-, variety-and process-specific algorithms, equipment training and significant capital investment are necessary to optimise the colorimetric defects classification and rejection criteria.]

Research

- On-line or near-line colour measurement

Sliced and dough-based potato crisps, snacks and crackers

Continuous measurement of finished product colour may be (if properly calibrated) a reasonably reliable predictor of finished product AA levels and could be used as a reference to demonstrate the effectiveness of an FBO's controls.

[Note: Continuous measurement is more relevant for sliced potato crisps, as such products (due to variability within the tubers) will be less homogeneous than a product made from a potato dough. Commission Regulation (EU) 2017/2158 allows analysis of AA to be replaced by measurement of product attributes (e.g. colour) or process parameters provided that a statistical correlation can be demonstrated between the product attributes or process parameters and the AA level. It is however the current industry understanding that, at least for potato crisps, colour alone cannot and should not be used as a substitute for sampling and analytical tests.]

Other considerations

As part of GMP, manufacturers should implement controls that may have an indirect impact upon AA levels in the final product, e.g. management of oil quality to ensure cooking temperatures are optimally maintained.

Removal of 'fines' from frying oil should be part of GMP to avoid any dark, over-cooked pieces present in the pack.

Root vegetable-based snacks

Within the context of this toolbox, root vegetable-based snacks are defined as products consisting wholly or mainly of tubers, storage roots and/or taproot vegetables. Most of these products are washed, sliced, and fried or co-fried to a low moisture level and crisp texture, allowing shelf-stable storage and consumption with no further preparation required from the final consumer.



Products may consist of a single-ingredient product (e.g. sweet potato crisps), or may comprise a mix of two or more vegetable species, and may even include sliced potato crisps or other potato or cereal dough-based snacks. These mixes can be fried individually or co-fried, which is a significant AA mitigation challenge due to geometrical and moisture diffusion challenges.

Within the European market the most used ingredients are the following vegetable species:

- Beetroot (*Beta vulgaris* subsp. *vulgaris*)
- Carrot (*Daucus carota* subsp. *sativus*)
- Parsnip (*Pastinaca sativa*)
- Sweet potato (*Ipomoea batatas*)

Information on further vegetable species (e.g. kale, seaweed, broccoli, etc.) may be included within a future revision of the toolbox if the market changes, if there is evidence that levels within these products are elevated, and if new tools become available.

At the present time, the European market for these products is very limited when compared with either potato-or cereal-based snacks, and mitigation tools are still at a research level.

Tools will be very process-, product-and ingredient-specific. FBOs should be encouraged to review all available research tools and report back on their success or otherwise in applying these within a commercial environment. The magnitude and feasibility of traditional potato crisp mitigation levers should not be assumed to be equivalent or directly transferable to root vegetable snacks.

Recipe

Research

Homogeneous shapes and sizes might favour stability across the entire processing line, which could result in more consistent AA outcomes.

A uniform flesh colour (preferably white to yellow) with low levels of surface defects (e.g. root hairs) may support better colour sorting of finished product.

Sweet potato finished product colour is highly impacted by flesh colour. The darker the flesh colour, the darker the colour after frying, with red flesh turning black after frying. This might present challenges in calibration of in-line optical sorters and development of manual sorting standards aimed at mitigating AA.

When incorporating vegetable powders (e.g. carrot) into starch/flour-based crisps that are sheeted and baked, AA must be considered and evaluated to avoid failure of product design. Asn, reducing sugar, and pre-existing AA levels vary by variety and form of the vegetable ingredient.

Process

Development

Blanching

Blanching of sweet potato slices before frying has shown the potential to lower reducing sugar levels, reduce AA levels, and reduce AA results variability.

Sweet potato blanching may be used alone or in combination with other AA mitigation levers (e.g. non-thermal slice pre-treatments, low temperature frying).

Changes in sensory attributes (e.g. flavour loss, texture change) might limit consumer acceptance.

Frying

At pilot scale, vacuum frying offers the possibility to significantly reduce AA formation in root vegetable crisps by enabling frying profiles with low temperatures. Vacuum frying may not deliver desired product attributes given the lack of Maillard compounds formed. Additionally, vacuum frying leads to much harder products and significantly changes the product characteristics.

High capital investment and operational costs prevent its viability.

Pairing par-frying with low temperature-finish drying has been shown to reduce AA and deliver a desirable texture to sweet potato crisps at pilot scale.

FBOs should aim to fry at the lowest possible temperature and time combination while meeting a finished product moisture content that delivers on consumer acceptability.

[Note: The fryer exit temperature should be as low as feasibly possible on a specific line and for the specific product, in line with expected quality and food safety standards, and considering all relevant factors.]

This toolbox does not set a specific fryer exit temperature target as this could be restrictive to an FBO's ability to manage AA in their finished products. FBOs should have the freedom to determine target fryer exit temperatures depending on their product design.

However, it should also be noted that target fryer exit temperatures are already established within Commission Regulation (EU) 2017/2158 for similar products.

Research

Peeling

FBOs should consider the impact of peeling on overall AA levels. This might be highly dependent on the root vegetable variety and season.

Processing: Finished product colour

Development

- In-line colour (optoelectronic or manual) sorting can be an effective measure to remove darker products which may in turn have a higher AA level
- Finished product colour

Elimination of darker-coloured products by in-line colour sorting (optoelectronic or manual) has proven to be an effective measure to reduce AA in potato crisp lines, and the technology may be useable in some root vegetable-based snacks products.

However, automated optical colour sorting of defects is extremely challenging for some products. For example, a beetroot crisp that is naturally very dark would be rejected as an outside-specification (e.g. black) sweet potato or parsnip crisp. Consequently, this mitigation measure should not be seen as a mandatory requirement for all vegetable-based snack products.



French fries and other cut, (deep-fried) potato products



Agronomy: Reducing sugars

General considerations

Reducing sugars are one of the key reactants for the formation of AA. The reducing sugar content of the tuber correlates well with the AA concentration in the product, especially if the fructose/Asn ratio is <2.

The concentration of reducing sugars is generally regarded as a good indicator of the relative AA-forming potential of different batches of tubers of the same potato variety.

Commercial application

- Minimising reducing sugars is part of standard manufacturing practices in the industry
- Control of tuber storage temperature identified as good practice
- Use of sprout suppressants, where legally permitted, to prevent sweetening during storage

Controlling reducing sugar is currently the primary measure employed by the industry to reduce AA levels in French fries. This is achieved through:

- Selection of potato varieties with low reducing sugars that are suitable for the product type
- Minimising the risk of high reducing sugars by growing those low sugar varieties best suited to the local growing conditions, by appropriate field selection, and by adherence to agronomy best practice
- Ensuring tubers are mature at time of harvesting (immature tubers tend to have higher reducing sugar levels)
- Selecting lots based on colour assessment of a fried sample, as there is a good correlation between reducing sugar content and final fried colour
- Controlling storage conditions from farm to factory, e.g. temperature (at least above 6°C for long-term storage, but temperature specified for the individual potato variety stored), and managing humidity to minimise senescent sweetening
- Reduction of tuber sprouting with permitted sprout suppressants or techniques and following GAP
- For potatoes stored at lower temperatures, reconditioning at higher temperature (e.g. ambient) over a period of a few weeks

[Note: Some manufacturers have reported that for some specific potato varieties it is necessary to store potatoes at temperatures at >8°C, and that with good storage controls it is possible to keep them in good condition for longer periods of time without relying on higher amounts of sprout suppressant treatments. Storage conditions should always be appropriate for the specific variety.]

Future considerations

- Breeding new potato varieties with lower reducing sugar content and/or less susceptibility to cold-induced sweetening
- Further optimise agricultural practices to minimise reducing sugars and Asn

Agronomy: Asparagine

Development

Selection of crop varieties on the basis of typical free Asn:total free amino acids ratio

Recent research suggests that the impact of farming practices (e.g. fertiliser regimes) may have an effect on amino acid ratios in potatoes. Sulphur deprivation may alter the ratio of free Asn:total free amino acids in a tuber and research has suggested that this ratio is potentially of greater significance to the formation of AA in potatoes than previously thought, in particular in the Asn:Gln ratio.

So far, no optimum amino acid ratio in potatoes has been established.

Research

Control of Asn levels in tubers

Farming practices, e.g. fertiliser regimes

Laboratory and field studies with new potato varieties

Asn, an important amino acid for plant growth, is the other key reactant for AA formation. In potatoes, Asn is the most abundant free amino acid, typically 0.2–4% dry weight, and 20–60% of total free amino acids. Asn levels do not correlate to reducing sugar levels.

Also, on its own, the reducing sugar concentration of potatoes is not always directly proportional to the AA concentration observed in a potato product. The concentration of free Asn and the ratio of free Asn to other free amino acids (of which Gln is by far the most abundant) should also be considered and may be better indicators of the relative AA risk of different potato varieties.

So far, no control of Asn levels in potatoes has been established. Potential leads being explored include:

- Breeding of lower Asn varieties
- Impact of storage on free Asn levels
- Impact of farming practices (e.g. fertiliser regimes) on Asn:amino acids levels.

In potatoes, the effect of sulphur is uncertain, and any advice on sulphur fertilisation to farmers would be premature based on the studies conducted so far.

An increased ratio of other amino acids to Asn results in competition for reactants during the Maillard reaction, potentially affecting the proportion of AA formed in the overall Maillard process.

In field trials in the USA, new potato varieties with silenced Asn synthase genes in the tuber have up to five-fold reduced amounts of free Asn. Heat-processed products derived from such tubers show comparable sensorial properties to their conventional counterparts, and much lower levels of AA (50–75% reduction). These varieties, two of which are now available for commercial cultivation, are considered GMO.

At the time of writing such potatoes are not yet approved for commercial production in the EU; therefore, the regulatory status should be checked.

General considerations

- Effect of optimisation of the reducing sugar content in the raw materials on other components influencing nutritional properties
- Minimising reducing sugar content needs to be balanced against processing methods and final product characteristics (colour, flavour, etc.)
- Elimination of defective materials as part of standard GMP has proven to be an effective measure to reduce AA in the final product. For example, this can be done through working with suppliers to ensure that incoming potatoes are checked whilst in storage, and again at plant, for defects (e.g. bruising and damage, viruses such as spraing/tobacco rattle virus (TRV), fungal diseases, storage rots).

Recipe: Other minor ingredients (amino acids, calcium salts and co-ingredients)

Development

Amino acids

In laboratory trials Gly was not successful in lowering AA.

Calcium salts

Despite promising results on laboratory scale, calcium lactate did not give satisfying results when tested on an industrial scale.

Recipe: pH

Development

Addition of low levels of acids to raw materials has shown synergistic benefits with calcium salts in small-scale pilot trials for crisps. However, the same tests for French fries at laboratory scale showed serious sour off-taste.

The use of acidulants (acetic, citric acids, lactic acid) and ascorbic acid in the French fry industry proved to be promising at laboratory scale as a mitigation tool.

However, their application in industrial French fry production did not result in additional AA reductions compared with the standard product, or the effect remains to be confirmed. Moreover, great care must be taken in order to avoid sour off-taste.

Recipe: Dilution and piece size

Commercial application

- Thicker strips decrease surface-area-to-volume ratio, reducing surface formation of AA

AA is formed on the surface, and surface-area-to-volume ratio affects the quantity of AA formed. Decreasing the surface-area-to-volume ratio by creating thicker strips/sticks of potato could be one way of reducing AA. However, the strip cut dimension is specified by customers.

Processing: Asparaginase

Development

- Asparaginase may reduce AA in an optimised laboratory environment; however, this differs significantly from an industrial setting

Despite the fact that asparaginase reduced the AA content of the final product in preliminary laboratory experiments, the application in the industrial production of frozen par-fried French fries could give various results. Some AA reduction as well as no reduction was found during pilot-line or industrial tests, depending on the conditions of application of the enzyme.

In a production line of blanched (non-par-fried) chilled potato strips, longer enzyme-substrate contact time is allowed, which leads to total Asn depletion for the enzyme-treated fries after four days of cold storage.

Asparaginase may be provided by the use of enzyme preparations or non-GM baker's yeast containing asparaginase enzyme activity.

Processing: Thermal input and moisture

General considerations

Moisture content has a strong influence on the activation energy of browning and AA formation. At low moisture contents, the activation energy for AA formation is larger compared to the one for browning. This explains why the end-phase of the frying process is critical and must be carefully controlled at a lower product temperature to optimise colour development and minimise AA formation.

For potato products including French fries, the finished frying/oven-cooking of the pre-fried potato product is done by the professional end-user or by the consumer at home (see guidelines under **Final preparation** below).

Commercial application

- For French fries, final preparation conditions are key as AA is formed during final cooking

Par-frying does not produce significant levels of AA in the semi-finished product, nor does it determine the level in the final product.

Other considerations

Effect of reducing the frying temperature on the fat content of the finished product (for example, with 9 mm fries, lowering the final frying temperature can lead to an increase in fat when frying to the same colour endpoint)

Effect of incomplete cooking on moisture level in products may have a subsequent impact on product quality, shelf life, and/or microbiological damage

Processing: Pre-treatment (e.g. washing, blanching, divalent cations)

Commercial application

- Blanching of potato strips/ pieces prior to processing
- Disodium pyrophosphate (SAPP)

The blanching process is the most important tool to control the reducing sugars (by removing and/or adding) to the required level of the colour of the specification of the final product and thus AA. Blanching removes sugars in the outer surface layer of the potato strip.

Addition of disodium pyrophosphate (SAPP) directly after blanching of French fries is used to avoid discolouration of uncooked strips and has a secondary effect of reducing AA by lowering pH, which inhibits the Maillard reaction. SAPP is not permitted in the production of organic French fries in the EU.

Processing: Finished product colour

Commercial application

- Measure and manage finished (fried) product colour after final cooking to colour specification

A study conducted by Ghent University on the main parameters (reducing sugar content and colour evaluation) linked to AA in the final product revealed that the best correlation was achieved by colour determination (using an Agtron process analyser).

The cooking instructions on the packaging have been revised to achieve a golden-yellow colour for the finished product.

Following these revised optimised cooking instructions results in lower AA levels.

It has been identified that in some European countries, consumer preference for French fries is to have them cooked to a golden-brown colour rather than golden-yellow. It is to be noted (or reminded) that final preparation and therefore final colour of the product is under the responsibility of the consumer/customer.

Use of food colourings as an ingredient in industrially produced products could be an effective tool to produce golden-brown French fries in some countries. However, there are legal constraints on the use of food colourings in plain potato products in certain regions (e.g. EU).

Lighter-coloured French fries can be an acceptable product for consumers if other organoleptic properties such as taste and texture are managed.

Other considerations

As part of standard quality procedures, manufacturers should implement controls which may have an indirect impact upon AA levels in the final product, e.g. management of oil quality to ensure cooking temperatures are optimally maintained.

Modification of texture and flavour are not directly suitable as a tool to reduce AA but are impacted by other interventions.

Final preparation: Consumer and restaurant guidance

Commercial application

Advice to chefs and consumers

Follow exactly the product-specific cooking instructions on the packaging.

Frying products

- Cook at maximum 175°C for prescribed time
- Do not overcook
- Cook to a golden (yellow) colour
- When cooking small amounts, reduce the cooking time

Oven products

- Preheat the cooking device (e.g. oven, air fryer) to correct temperature to between 180–220°C according to on-pack cooking instructions, depending on the product specifications and local requirements
- Cook at 180–220°C for prescribed time
- Cook to a golden (yellow) colour
- When cooking small amounts, reduce the cooking time.

European Potato Processors' Association (EUPPA) developed a specific tool presenting "Good frying Practices" to help consumers and restaurants, which can be seen at **www.goodfries.eu**.

On the website you can find more information on EUPPA recommendations on how to prepare French fries and other potato products. It is recommended to avoid cooking methods in which the temperature cannot be measured. Other mitigation measures for products different from French fries, such as home-made fries, hashbrowns/rosties, pomme croquette, pomme noisette, and pomme duchesse, are updated regularly on the Good Fries website.

The U.S. Food and Drug Administration also has a webpage listing the ways to reduce AA: Acrylamide and Diet, Food Storage, and Food Preparation.

Development

▶ "Fresh" prefabricated French fries may have higher sugar contents toward end of product shelf life if blanching time is too short

A study performed in Switzerland has shown that "fresh" prefabricates of blanched French fries and hash browns stored at 4°C until end of shelf life had relatively higher amounts of reducing sugars versus the same products that were kept frozen. The authors claim that residual enzyme activity (α-amylase) may slowly release reducing sugars during cold temperature storage.

The very short blanching time (five minutes) used in this study is not representative of industrial production of chilled or deep-frozen French fries (10–45 min).



Cereal/grain based products

(Fine bakery wares and breakfast cereals)



Agronomy: Reducing sugars

General considerations

The reducing sugar composition of cereal grains is not a key determinant of AA formation and is therefore not considered relevant in the context of reducing AA in fine bakery wares and breakfast cereals.

Commercial application

Sugars composition of cereal grains is of less impact than the Asn level in the raw materials[1]

Research confirms that Asn rather than sugars is the key determinant of AA formation in cereal products. Free Asn levels have been found to have a much greater impact than the levels of reducing sugars in wheat.

Measurements for four soft wheat varieties in 2004 found 0.9–1.3% dry weight of total reducing sugars comprising glucose (0.41–0.58%), fructose (0.17–0.2%), and maltose (0.36–0.55%). Sucrose was at 0.5–0.65%. AA formation showed no relation to total reducing sugars or to individual sugars concentration. Recent work has shown a wide variation of reducing sugars in different cereal grains and their fractions; for example, fructose/glucose amounts are highest in wholemeal rye/wheat.



1 Acrylamide: Update on Selected Research Activities Conducted by the European Food and Drink Industry, TAEYMANS ET AL.: JOURNAL OF AOAC INTERNATIONAL VOL. 88, NO. 1, 2005

Agronomy: Asparagine

General considerations

Asn is the critical component leading to the formation of AA in cereal products. Research shows that free Asn varies widely within one single variety, between cereal varieties, and also according to growing conditions on individual fields (impacted by e.g. sulphur levels). This is confirmed by university research on heated wheat flour, where it has been shown that free Asn concentration is the key determinant. Because of the sources of variation (grain type, variety, growing conditions, climate), it is impossible to source wheat or any other grain with controlled low levels of Asn.

Moreover, depending on the type of grain used, a product has specific characteristics defining the product identity. Consequently, it is not possible to simply replace the grain by another grain without changing the product identity.

For these reasons, more fundamental knowledge is needed concerning the impact of agronomical practices and cereal varieties on Asn level. Therefore, industry partners support research proposals that aim to investigate breeding science to control Asn in wheat varieties.

After receiving industry trade association submission, the European Cooperation in Science and Technology (COST) approved COST Action CA21149 (ACRYRED, https://acryred.eu/). This initiative has successfully established a comprehensive multidisciplinary research and communication network. The aim of the initiative is to minimise the AA exposure of consumers by a cereals supply-chain approach that specifically targets Asn in grains. This approach encompasses the entire value chain from grains to consumer products. If Asn levels can be reduced through better breeding and farming practices, it is anticipated that downstream AA formation in cereals-based products can be reduced more effectively.

The development of grains with consistently low levels of Asn poses several challenges to overcome. These challenges encompass various aspects, including potential concerns regarding new varieties. Factors such as yield, disease resistance and milling performance need to be carefully considered to ensure the overall success of this endeavour. Furthermore, regulatory clearance can be a hurdle and needs to be addressed as well as potential risks of limited acceptance or resistance from various stakeholders, including consumers, farmers, breeders, and manufacturers. It is essential to engage and address the concerns of all stakeholders to foster a collaborative and supportive environment for the implementation of this initiative.

FBOs should keep abreast of progress on research to breed new, low-Asn wheat through relevant trade associations and research institutes.

Commercial application

- Farmers should be aware of the importance of maintaining balanced sulphur levels for cereal cultivation
- Farmers should avoid late and excessive application of nitrogen in consistency with GAP on fertilization
- Farmers should be guided to use appropriate crop protection measures to prevent fungal infection in consistency with good phytosanitary practices

Free Asn levels in cereals can become elevated during plant development when the plant is grown under stressed conditions, particularly in sulphur-deprived soils, which then results in a higher risk of AA formation.

Late application of nitrogen may increase free Asn and total free amino acid concentration in wheat and other cereals, causing a concomitant increase in AA-forming potential. Nitrogen fertiliser is required to maintain the yield and quality of the crop, but excessive application should be avoided.

Fungal pathogen infection causes a significant increase in free Asn concentration in cereal grain. It is therefore important to apply best practices on crop protection measures to prevent fungal infection.

Development

- Choice of wheat varieties
- Lowering the proportion of wholegrain and/or bran in products will significantly impact nutritional quality and organoleptic properties of the product

Breakfast cereals

Choice of wheat with lower free Asn has led to products with lower AA levels, but current experience suggests that it is not yet possible to specify low free Asn wholegrain. Using less wholegrain (lower bran and germ) and more endosperm will be effective (as free Asn is more concentrated in the germ/bran) but will significantly compromise the product's organoleptic and nutritional properties.

Most wheat-based breakfast cereals are made from soft wheat. Although soft wheat typically has lower protein content than hard wheat, the presence of other free amino acids may influence AA formation through competition with free Asn during the Maillard reaction.

After a three-year trial by one manufacturer, it appears that environmental variation between growing sites is too great for such selection to work on a large industrial scale. For further information, please refer to the full chapter on breakfast cereals, found later in this toolbox.

Cereal-based products

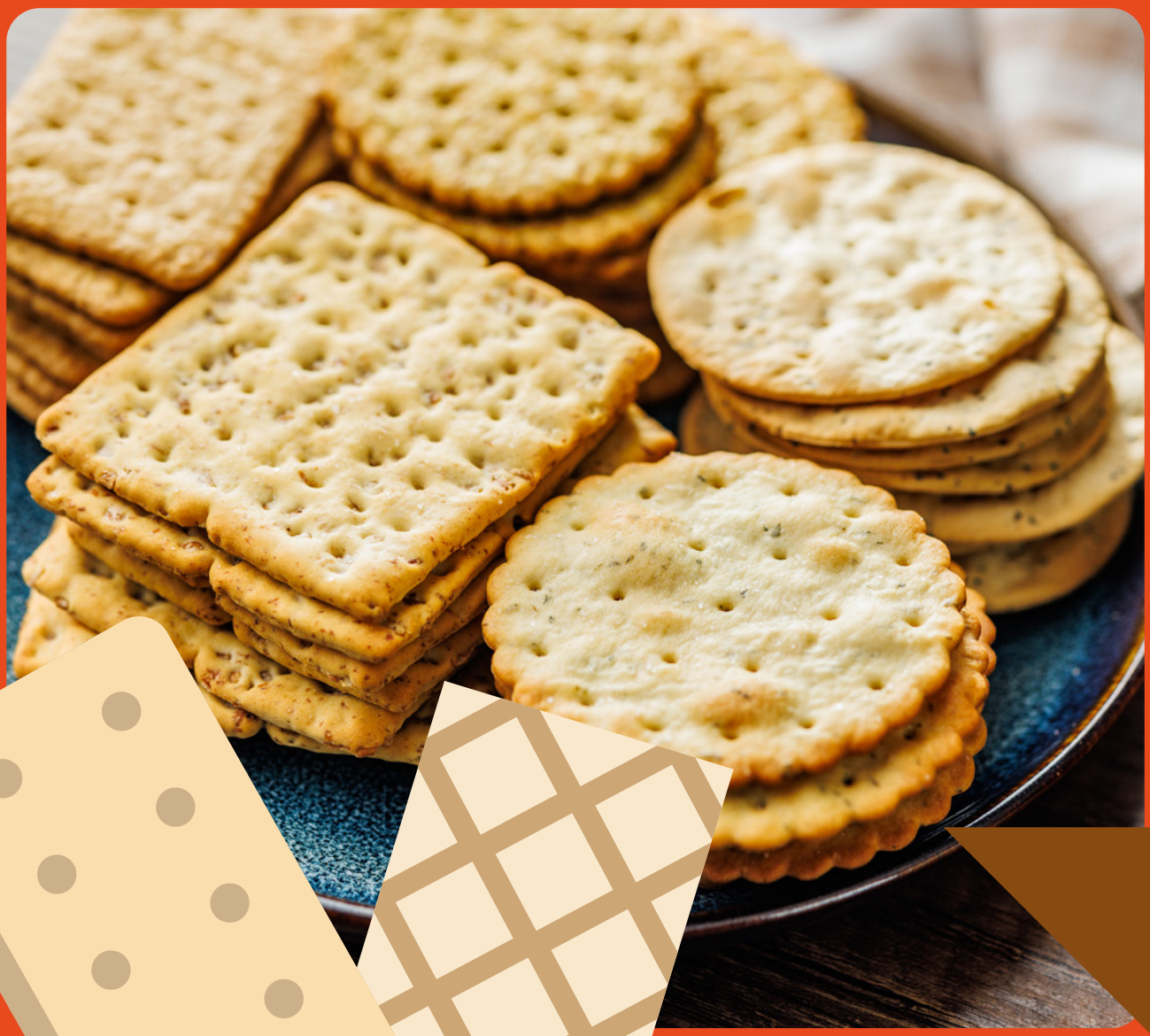
Current experience suggests that specifying low free Asn wholegrain is not yet possible, but that using less wholegrain and/or bran and more endosperm will be effective (as free Asn is more concentrated in the germ/bran) but will significantly compromise the product's organoleptic and nutritional properties. Reducing the nutritional quality of cereal-based products (e.g. less wholegrain, fibre and other beneficial nutrients) would negatively impact their consumption, in the worst case exacerbating deficiencies. It needs to be considered that cereals are major contributors to the consumer's intake of fibres.

Crispbread

Analysis of rye samples has shown that environmental factors have more influence than rye variety. It has not been possible so far to identify which environmental factors have the most significant effect. Statistically robust sampling protocols must be in place for the validation of new cereal/grain varieties to ensure that AA levels of finished products continue to be ALARA. It must not be assumed that any variety, crop season, or geographical origin of a crop is by default equivalent to the incumbent supply.

Fine bakery wares

(Biscuits, crackers, wafers, crisp bread and gingerbread)



This toolbox section covers products as defined according to Part E of Annex II to Regulation (EC) No 1333/2008 on Food Additives. This category covers *"sweet, salty and savoury products, including prepared doughs for their preparation, such as cookies, cakes, muffins, doughnuts, biscuits, rusks, cereal bars, pastries, pies, scones, cornets, wafers, crumpets, pancakes, gingerbread, éclairs, croissants, as well as unsweetened products such as crackers, crispbreads and bread substitutes. In this category a cracker is a dry biscuit (baked product based on cereal flour), e.g. soda crackers, rye crisps, matzot:"* https://food.ec.europa.eu/system/files/2022-12/fs_food-improvement-agents_guidance_1333-2008_annex-2.pdf

Recipe and product design: Wholegrain products

Development

- Choice of wheat varieties
- Lowering the proportion of wholegrain and/or bran in products will significantly impact nutritional quality and organoleptic properties of the product

Free Asn is the key determinant of AA formation in cereal products. Accordingly, using wheat with a lower free Asn content has a lower AA potential.

However, it is currently not possible to specify for low Asn in cereal grains, including for wholegrain products.

Using less wholegrain and/or less bran and germ and more endosperm may result in lower AA levels (as free Asn is more concentrated in the germ/bran) but will significantly compromise the product's organoleptic and nutritional properties.

Recipe and product design: Raising agents

Commercial application

- Reducing or replacing NH_4HCO_3 in recipes as used in certain commercial applications is an option to lower AA, but the impact on organoleptic properties must be assessed

Replacing (fully or partly) NH_4HCO_3 with alternative raising agents (such as sodium bicarbonate and acidulants, sodium bicarbonate and disodium pyrophosphates with organic acids or potassium variants thereof) is a demonstrated way to relatively lower AA in certain products and on a case-by-case basis.

Despite changes to flavour, colour and texture, several products (sweet biscuits and gingerbread) have been reformulated and commercialised. In most cases, sodium salts were the replacement. However, to achieve the correct balance of gas release during baking, and optimum texture, flavour and colour, combinations of NH_4HCO_3, $NaHCO_3$ and acidulant are often required.

Experiments have shown that NH_4HCO_3 can promote the production of AA in gingerbread. NH_4HCO_3 increases the formation of sugar fragments (glyoxal and methylglyoxal) that react rapidly with Asn to furnish AA in higher yield than the native reducing sugars under "mild" conditions.

Considerations should include that changes may result in organoleptic (taste, appearance, texture, etc.) or nutritional changes (increased sodium content) that influence product identity and consumer acceptance.

Recipe and product design: Asparaginase

Commercial application

- Manufacturers shall consider using asparaginase to reduce Asn to mitigate the potential for AA formation

The use of asparaginase is proven to be one of the most efficient tools to reduce AA levels and if used at low dosage rates has no negative impact on the organoleptic properties of the final product.

For consideration, the efficacy of asparaginase is dependent on recipe, ingredients, moisture content and process (temperature, pH, time, distribution in dough), and therefore differs from product to product. In particular, experience shows that there is limited or no effect in recipes with high fat content, low moisture or high pH value.

Asparaginase may be provided by the use of enzyme preparations or non-GM baker's yeast containing asparaginase enzyme activity.

Recipe and product design: replacing wheat flour with alternative grain types

Commercial application

- Different types of grain are typically different in Asn levels. Therefore, a partial replacement of cereal flour with an alternative grain flour may be an option

Crispbread

If crispbreads are produced with cereal grains that are low in Asn, then consequently products low in AA are expected.

Where technologically feasible, the proportion of ingredients with higher free Asn concentrations can be reduced through formulation changes. For example, in one commercial product, rye flour type 1800 was replaced with rye flour type 997, which contains less bran and germ material, i.e. less free Asn.

However, while Type 997 may have a lower content of free asparagine, this is not always the case. The replacement of type 1800 or wholemeal flour with type 997 is therefore not feasible for every crispbread. In addition, depending on the choice of the raw material, this may change the product composition, nutritional values and characteristics considerably, especially in the case of wholemeal products.

Short, sweet biscuits

Where a product characteristic allows, manufacturers shall consider a partial replacement of wheat flour with alternative grain flour such as rice.

For consideration, any change will have an impact on the baking and organoleptic properties. Different types of grains have shown different levels of Asn (typical Asn levels: rye > oats > wheat > maize > rice).

The partial replacement of wheat flour by rice flour may be an effective measure when acceptable from a quality perspective. In particular for baby biscuits, consideration should be given to the potentially higher arsenic level in rice compared to wheat.

Recipe and product design: Co-ingredients

Development

- Heat-treated co-ingredients such as roasted/toasted nuts and oven-dried fruits may contribute to the AA level in the final product

Manufacturers shall consider the impact of co-ingredients that may have the potential to raise AA levels in the final product (e.g. roasted almonds; dried fruits and vegetables as potential fructose sources).

Manufacturers shall have a change control procedure in place to ensure that a change in products sourced from suppliers does not result in inadvertently increased AA levels.

Manufacturers shall ensure that suppliers of heat-treated ingredients susceptible to AA formation provide an ingredient AA risk assessment and implement the appropriate mitigation measures.

Recipe and product design: Minor ingredients

Commercial application

- Replacing fructose with glucose is very effective in reducing AA formation, particularly in recipes containing ammonium bicarbonate

For relevant products and where the product design allows, replacing fructose or fructose-containing ingredients (e.g. syrups, honey) with glucose or non-reducing sugars (e.g. sucrose) is seen an effective tool to reduce the AA formation, particularly in recipes containing ammonium bicarbonate.

Reducing sugars are responsible for many of the characteristic flavours and colour in sweet biscuits. Fructose replacement by glucose retained original quality and texture in several commercial applications at a paler colour.

When glucose-fructose syrups are used, the fructose content should be as low as possible.

Therefore, considerations should include that replacing fructose or other reducing sugars may result in a modified product identity due to loss of flavour and colour formation.



Development

- Gly addition impacts sensorial properties
- Calcium salts give variable results and have adverse flavour effects

Gingerbread

Gly addition (1% in the recipe) decreased AA content ~2.5-fold and enhanced browning, but with a clear impact on the sensorial properties of the product.

Trials at bench scale with added calcium salts give variable results, most affecting product quality. Not seen as an option for application on commercial plant level.

- Gly addition changes product colour/quality

Short, sweet biscuits

Gly addition changes product colour and produces products of unacceptable quality.

- Addition of Gly and calcium impact negatively key quality attributes

Crispbread

The level of AA can be affected by Gly at 3% (w/w) resulting in a reduction by approximately 78%. However, the colour may be affected and an undesirable sweet flavour introduced. Ca2+, whilst only slightly reducing AA, has an adverse effect on the flavour and texture at pilot plant level.

Development

- Addition of organic acids may be effective in combination with other potential mitigation measures. Application of this option is limited by resulting organoleptic changes

The addition of organic acids/adjustment of pH in combination with other recommendations may result in lower AA levels. Decreasing the pH will influence the Maillard reaction in the direction of decreased AA formation. However, this option is limited by resulting organoleptic changes (less browning, modification of taste).

Biscuits, crispbread, gingerbread

In the absence of ammonium raising agents, pilot-scale studies on biscuits have shown that pH and AA follow a linear trend with a reduction in AA of about 17% per unit drop in pH.

In laboratory experiments with an intermediate product (semi-sweet biscuit), a 20–30% reduction of AA was achieved by adding citric acid to reduce the pH.

Addition of citric and tartaric acid (~0.5% in the recipe) decreased AA content approximately three-fold in gingerbread versus a control but resulted in a product of insufficient quality (acidic taste, less browning). In crispbread and biscuits, the pH has an impact on the organoleptic properties of the final product.

Models have shown that in certain bakery products, lower pH in combination with fermentation can lead to an increase in another undesired process contaminant (namely, 3-MCPD).

Recipe: Shape and piece size – biscuits, crispbread

Commercial application

- For new product development, manufacturers shall consider piece size/surface-area-to-volume ratio during product design, as small product size potentially leads to higher AA levels

In biscuits and crispbreads, the thicker the product, the lower the AA levels. This, however, significantly changes the product's characteristics.

Processing: Fermentation

Commercial application

- Lower levels of AA in fermented products. Extension of fermentation time in bread may be an option to lower AA levels

Crispbread

Some baked products, such as crispbreads and crackers, can be made from fermented dough so as to develop specific textures and flavours. Compared to similar non-fermented products, the level of AA in the fermented variants is generally lower. Yeast rapidly assimilates Asn and aspartic acid, as well as sugars. Crispbread, which is mainly produced with yeast, also shows significantly lower AA content for fermented variants versus cold bread (non-fermented variants). In crispbread manufacture, other factors such as biscuit thickness and baking conditions must be seen in perspective.

- Extended yeast fermentation time may be an option but warrants further study
- Use of lower-gassing yeast to decompose Asn faster

Sweet biscuits and crackers

Biscuit and cracker dough: long yeast fermentations are an effective way of reducing Asn levels. Fructose levels increase at moderate fermentation times, but the yeast later absorbed this, so the net effect on AA was beneficial.

However, no studies on increasing fermentation time in crackers were reported in the latest Association of the Chocolate, Biscuit and Confectionery Industries of Europe survey.

The use of lower-gassing yeast may be a mitigation option in some products since the latter is independent of Asn consumption. As more yeast activity is added, this results in a faster decomposition of Asn at the same overall gas generation rate. Non-GM baker's yeast containing asparaginase activity are specifically relevant in this area.

Processing: Thermal input and final product moisture

Commercial application

- Optimisation of thermal input has resulted in a reduction of AA

Manufacturers shall control thermal input by optimising baking temperature, temperature profile and time.

As guidance, controlling thermal input through temperature and time is essential rather than temperature alone to control product characteristics and AA formation. Solutions may vary depending on the particular product and capabilities of existing processing equipment.

Crispbread

In non-fermented crispbread, reduction in process temperature and oven speed reduced AA by approximately 75%. The most important impact comes from ensuring the end humidity levels are as high as is tolerable from a quality point of view. However, other products may suffer significant changes to colour, flavour and texture.

Processing: Finished product colour

Commercial application

- Manufacturers shall consider baking to a lighter colour endpoint in the final product if feasible to achieve the required quality, shelf life and food safety standards

Hard sweet biscuits, crispbread, breakfast cereals, bread substitutes

The Maillard reaction, which leads to the production of AA, also produces the colours and flavours which give baked cereal products their essential characteristics. However, if lighter-coloured and less-baked products could be produced without increasing moisture content, the AA level could theoretically be reduced.

Colour endpoint is an approach applied for (i) hard sweet biscuits with a reported ~10% reduction in AA and lighter colour, and (ii) crispbread through reduced "final roast" with acceptable reduction in browning.

Appropriate algorithms, equipment training and significant capital investment are necessary to optimise the colorimetric rejection criteria.



Processing: Texture/flavour

Development

- Manufacturers shall consider increasing the moisture specification for the final product if feasible for the particular product and process, in line with achieving quality (including physical properties), shelf life and food safety standards

Biscuits

The reaction leading to the formation of AA (the Maillard reaction) is also the reaction which develops flavour and colour. In some products (e.g. gingerbread), sugars, such as glucose or fructose, are deliberately added so as to achieve particular flavours (and colour). Such products also tend to be higher in AA. Avoiding the addition of reducing sugars would reduce the amount of AA, but at the expense of flavour development.

Products baked at a high temperature and to a low final moisture content, so as to have a crisp texture, tend to be higher in AA. Products such as shortbread, which are baked at low temperature and for a long time, are lower in AA. Individual studies are warranted to assess feasibility and acceptance tolerance.

Processing: Rework

Commercial application

- Manufacturers shall adjust product and process design to account for ingredients that could be heat treated several times and as a result raise AA levels in final products (e.g. pre-processed cereal pieces, nuts, seeds, dried fruits, etc.)

The use of small quantities of rework is common practice today if within the specified range for colour formation. Although it is known that in general avoiding rework is reported to have no significant benefit in reducing AA levels, manufacturers shall not use burnt products as rework.

Based on studies conducted in Germany, rework in certain bakery wares may have an impact on the amount of AA present in the final product.

In pilot studies with sweet biscuit dough, it has been shown that more AA is formed in biscuits baked from older dough (an increase of approximately 35% over 3 hours). The extra AA could be accounted for by the measured increase in free Asn over time. Therefore best practice should avoid dough ageing or reworking of aged dough where possible. However, the most recent survey shows that there is no evidence that elimination of rework provides any benefit in terms of AA reduction when applied on an industrial scale.

Other work conducted on non-fermented crispbread has shown no significant effect on the formation of AA in the product.

Final preparation

Commercial application

- Preparation instructions of product pre-mixes at home or in catering establishments need to be provided

Pack instruction

For product pre-mixes that are to be baked at home or in catering establishments, clear on-pack preparation instructions shall be provided to lead to levels below the benchmark levels.



Breakfast cereals

Products primarily manufactured from cereal grains (such as corn/maize, wheat, barley, rye, oats or rice) that are generally designed to be eaten with milk (hot or cold).



For agronomy, please refer to section on Cereal/grain-based products.

Recipe and product design: Wholegrain products

Commercial application

- Using less wholegrain and/or bran and more endosperm will significantly compromise organoleptic properties/product identity and nutritional quality of products with a negative impact on consumer intake of wholegrain, fibre and other beneficial nutrients

All of the major grains may be used in breakfast cereals, and some grains yield more AA than others within a common process. Different kinds of grains have shown different distribution of free Asn, e.g. products based on maize and rice tend to have less AA than those made with wheat, rye, oats and barley.

However, the choice of grain defines the food and therefore it is not possible to simply replace the grain by another grain without changing the whole product and losing the product identity the consumers like.

Recipe and product design: Reducing sugars

Commercial application

- Reducing sugars (e.g. fructose and glucose) and ingredients containing reducing sugars (e.g. honey) may contribute to the AA burden, if added prior to heat-treatment stages

Reducing sugars (e.g. fructose and glucose) and ingredients containing reducing sugars (e.g. honey) are sometimes added for organoleptic reasons and process functionalities (binding clusters for cluster formation).

If added prior to heat-treatment stages, they can act as precursors to AA formation. In this case, controls over addition rates must be established and implemented at point of addition.



Recipe and product design: Heat-treated ingredients

Commercial application

Heat-treated ingredients such as roasted/toasted nuts and oven-dried fruits may contribute to the AA level in the final product

Heat-treated dry-added ingredients may contribute to AA levels in the final product. Low-roast almonds contain less AA than high-roast almonds. Peanuts and hazelnuts contain less than a fifth of Asn almonds hold, so they yield much less AA. Where baked pieces are used in muesli, their recipe should be reviewed following the advice for biscuits.

The AA contribution from heat-treated dry-added ingredients (e.g. roasted/toasted nuts and oven-dried fruits) to the total AA value must be assessed in the hazard analysis critical control point (HACCP), and alternative ingredients considered if the contribution is likely to bring the finished product above the benchmark levels per Commission Regulation (EU) 2017/2158. For ingredients over 150 µg/kg AA, the assessment shall include:

a. a register of ingredients over 150 µg/kg AA

b. verification steps, e.g. audits of the supplier's HACCP and/or analyses

c. consideration of AA risks in the supplier's HACCP (by the supplier)

d. a change of control procedure to ensure that no changes are made that inadvertently increase AA levels (by the supplier).

Some dried fruits (e.g. prunes, pears) were reported to contain AA. Tests were therefore made of some ingredients commonly added to mueslis and flake-with-fruit cereals. Dried fruit and nuts may make up around 25–50% of muesli by weight; raisins and sultanas generally predominate.

There was no measurable AA in raisins of several kinds and origins, dried apple, dried cranberries, candied papaya or candied pineapple. Low levels were found in dried bananas, dried coconut and prunes.

Recipe: Asparaginase

Research

Using asparaginase to reduce Asn in breakfast cereals: further investigation required to overcome significant technical constraints to fully comprehend its capabilities and to work towards developing solutions to overcome these challenges

The use of asparaginase variants with limited heat stability has been found to be ineffective in reducing Asn in many breakfast cereals that undergo cooking and toasting with coarse grain cereal. This ineffectiveness is due to necessary time and temperature constraints at the industrial level, which prevent the appropriate conditions for the enzyme from significantly reducing Asn. Former trials at laboratory and pilot-scale in collaboration with an enzyme supplier have shown different levels of efficiency based on process design, type of grain, particle size of grain, moisture content, achievable time and temperature profile as well as other recipe parameters. The use of enzymes in breakfast cereal processes is difficult because of low moisture contents which makes enzyme penetration into the grain or food matrix difficult. Many breakfast cereal processes use coarse flours or chopped grains which are not readily penetrated by the enzyme. Typical processes for making breakfast cereals contain heating steps that lead to the de-activation of the enzyme.

Nevertheless, breakfast cereal manufacturers continue to investigate if asparaginase variants with limited heat stability can be applied in certain breakfast cereal processes and recipes – in particular, when the cereal is in a flour dough format and when the process enables sufficient time, temperature and moisture content for asparaginase to reduce Asn levels significantly (the latter provided there is no negative effect on flavour or risk of residual enzyme activity).

When research shows promising results, the scale-up of a process with asparaginase needs to be investigated. This may lead to significant process changes and may impact product quality.

One FBO has reported that the development of an asparaginase variant with improved heat stability has shown results in reducing AA in certain products. However, it is important to note that the application of these variants is currently hindered by a number of significant technical constraints as it is not universally applicable across all breakfast cereals due to its limited effectiveness in all unit operations. Despite the improved thermal stability of this enzyme variant, it still does not maintain its efficacy throughout the entire production process of many breakfast cereals. Conversely, in some breakfast cereals, there is a challenge of insufficient deactivation of the enzyme, leading to potential issues. Furthermore, the pH sensitivity of the enzyme in breakfast formulations presents additional limitations. Further investigation is therefore required to fully comprehend their capabilities and to work towards developing solutions to overcome these challenges.

Asparaginase may be provided by the use of enzyme preparations or non-GM baker's yeast containing asparaginase enzyme activity.

Recipe and product design: Minor ingredients

Development

- Sugars are usually added after the toast
- The impact of malt on AA formation
- Addition of calcium chloride and carbonate supports AA reduction
- Addition of Gly is not feasible
- Positive effect of antioxidants not evident

In breakfast cereal production, manufacturers in Europe generally use sucrose and small amounts of malt in the cereal itself because reducing sugars darken the cereal too much. Where alternatives to sucrose may be used, it should be verified that these do not increase AA levels. Added fructose tends to cause severe browning. Honey, glucose, fructose and other reducing sugars are generally used in the sugar coat applied after toasting so they do not influence AA formation.

One manufacturer reports that malt (specifically, malted barley) has been shown to reduce AA in breakfast cereals.

Further investigation has shown that, due to the variability of malted ingredients (some can result in very high sugar conversion, while others do not), this is an unreliable way of reducing AA. There are two sources of variability: a) the natural variability of malting factors, including roasting of grain, leading to a variable amount of reactants and antioxidants, and b) a broad class categorisation of malted ingredients.

One manufacturer reports that calcium chloride and calcium carbonate can reduce AA by 10% as proven in pilot plant studies. The flavour of the product appears to be acceptable for calcium chloride and calcium carbonate up to 0.4–0.5% of solids.

Precautions should be taken to ensure that other process contaminants (e.g. chloropropanols, 3-MCPD) are not formed as a result of this mitigation.

At pilot plant scale, Gly has been found to reduce AA formation by up to 50% in some types of wheat flake. The addition of Gly is limited by the formation of dark colour and a bitter taste. Due to the high reaction rate of Gly, even at the smallest addition levels, trials to date have not been successful in controlling the effect of Gly on colour, flavour and taste with requirements for product moisture, texture and shelf life. Manufacturers added Gly in the pilot plant with other amino acids (proline and lysine) and found that Gly and proline did reduce AA, but all three amino acids imparted an unacceptable bitter flavour to the product.

Additional investigation by a manufacturer came to the conclusion that the addition of Gly is not feasible.

Manufacturers also report pilot plant trials with antioxidants vitamin C and E, with no reduction found in AA. The effect of various other antioxidants such as green tea, rosemary or oregano was not confirmed as effective for industrial operations.

Research

- Addition of lysine is not a reliable tool for AA mitigation from pilot plant experiments

At pilot-plant scale, the addition of lysine has been found to reduce to a certain degree the formation of AA under modified processing conditions to produce a type of wheat flake. However, due to its impact on the sensory properties of the product, even at small addition levels, the addition of lysine does not represent a reliable way to mitigate AA.

Recipe and product design: pH

Development

- Reduction of phosphate salts can lead to less AA formation (limited applicability due to adverse effects on sensorial attributes)

Reduction of phosphate salts has been proven to reduce AA in breakfast cereals at pilot plant scale. However, this shows adverse effects over the sensorial attributes (colour, flavour, texture), which limits its applicability.

Processing: Thermal input and moisture

Commercial application

- Optimisation of thermal input has resulted in a reduction of AA in breakfast cereals
  - Do not over-bake or over-toast; avoid the incidence of burnt product
  - Identify the key critical heat-treatment step(s) to focus AA reduction/control efforts
  - Control heating temperatures, times and feed-rates to achieve typical minimum moisture contents after the final heat-treatment steps to help avoid the generation of AA spikes
  - It is important to measure the moisture content as well, and express AA concentration on a dry mass basis to eliminate the confounding effect of moisture changes

In general, higher heating temperatures and longer heating times generate higher AA levels. An effective combination of temperature and/or heating times minimises AA formation, without unacceptably compromising the taste, texture, colour, safety and stability (shelf-life) of the product.

The formation of AA during the baking of cereal products is closely related to the combination of moisture content and baking temperature/time (thermal input).

One manufacturer reports that for breakfast cereals, this concept was evaluated and results showed that AA correlates with moisture but does not correlate well with colour. Therefore, at constant moisture (for toasted products), AA is expected to be constant under conditions of breakfast cereal processing.

However, other manufacturers report that they evaluated lower heating temperatures and (separately) shorter heating times and, although both reduce AA, they also adversely affect product colour and taste. Different combinations of heating temperature and time were also examined, and it was found that all the combinations that produce an acceptable colour and flavour also have a similar AA level. This suggests that the scope to reduce AA by optimising thermal input may only be restricted to certain breakfast cereal recipe/process combinations.

AA content tends to be well correlated with moisture content of toasted products (as lower moisture content is usually generated by a higher thermal input), but manufacturers generally apply both maximum and minimum ranges for moisture as a part of routine quality management and raising the moisture content tends to compromise shelf-life.

Typical minimum moisture content (g/100g) for consideration:

- Toasted products: 1 g/100 g for extruded products, 1 g/100 g for batch cooked products, 2 g/100 g for steam rolled products
- Direct expanded products: 0.8 g/100 g for extruded products
- Baked products: 2 g/100 g for continuously cooked products
- Filled products: 2 g/100 g for extruded products
- Other drying: 1 g/100 g for batch cooked products, 0.8 g/100 g for gun puffed products

Measurement systems should be calibrated at least annually and these operating conditions controlled within set limits. These tasks should be incorporated into a HACCP pre-requisite program.

Recipe: Rework

Development

▶ There might be an impact of rework on AA levels under specific circumstances

Reworking products back through the process has the potential to generate higher AA levels through repeated exposure to the heat-treatment steps. Manufacturers shall assess the impact of rework on AA levels and, if significant, focus on reducing or eliminating rework.

Processing: Finished product colour

Research

▶ Colour is a characteristic property of many products, but selected products could be modified without reducing consumer acceptability, e.g. if they are subsequently chocolate coated

A correlation between AA and the colour in breakfast cereals is a case-by-case situation and could not be established generally.

However, manufacturers shall have procedures in place (e.g. temperature controls/monitoring) to prevent the incidence of burnt products, as this may give rise to consumer dissatisfaction and AA spikes.

Coffee



Agronomy: Reducing sugars

Development

- No correlation to AA formation

Sugar levels in the green beans (Robusta, Arabica) show no correlation to the amount of AA formed during roasting.

Agronomy: Asparagine

Development

- No mitigation options through crop selection due to narrow range of free Asn
- Contribution of marginal pathways not yet clarified
- Agronomic aspects not adequately studied and are considered long-term

Free Asn concentrations in green coffee beans lie within a narrow range, typically from 20–100 mg/100g, and thus do not provide the opportunity for possible control or reduction by selection of beans with relatively low amounts of free Asn. On average a tendency of slightly higher AA content in roasted Robusta beans has been reported, which in some cases may reflect the concentrations of Asn in the green coffee beans.

Other considerations

Other minor pathways not related to free Asn may become important for the formation of AA.

Processing: Asparaginase

Research

- Applying asparaginase enzymes in coffee may have application opportunities in particular for steam-treated coffees

The applicability of asparaginase enzyme treatment of green coffee is limited. The European coffee industry and enzyme suppliers have worked together in applied research and in practical trials to assess the use of asparaginase to destruct Asn, one of the major precursors of AA. The green coffee bean is a very dense, hardly permeable raw material and additional processing steps (steam treatment and soaking in a water bath) are required for the enzyme to be effective.

However, the steam treatment/enzyme treatment process has potential relevance only for a very modest fraction of coffee production. It affects the taste profile in a way that is not compatible with the desired sensory properties of the majority of coffee blends. Asparaginase treatment therefore cannot be expected to achieve serious AA mitigation percentages in overall coffee manufacturing.

In any further specific assessment, it is recommended to include the following findings and considerations:

- Trials as referenced in the above have been made under laboratory/pilot plant conditions only. Scaling up will require an assessment of the suitability of treatment conditions as applied in laboratory/pilot plants for application at commercial plant scale in line with GMP. The food safety aspects and impact on sustainability of the finished product should also be taken into account.
- Any green coffee enzyme process would be a new and additional process for roast coffee and soluble coffee manufacturing. This process cannot be integrated into the existing roast coffee manufacturing processes and will accordingly require new plants and facilities, except for potential capacities in existing decaffeination and green coffee steam treatment facilities after required adaptation to the enzyme process.

The acceptability of the impact on flavour has to be assessed on an individual case-by-case basis depending on green coffee type, the percentage of the enzyme-treated coffee in the total blend, and the specific quality targets of the product.

Asparaginase may be provided by the use of enzyme preparations or non-GM baker's yeast containing asparaginase enzyme activity.

Processing: Amidase

Development

Application of amidase enzymes in soluble coffee

Preliminary evidence suggests amidase potential to effectively reduce AA levels in soluble coffee, but further case-by-case testing is required to assess its broader applicability. It is important to note that amidase potential is limited to soluble coffee and does not apply to roasted coffee.

Regarding technical aspects, compatibility with existing production processes shall be considered to determine the suitability of amidase for broader use. Further consideration should be given to the enzyme's performance throughout the entire shelf life of target products and organic product restrictions also need to be considered.

Processing: Thermal input and moisture

Development

Roasting technologies beyond existing ones have been tested, but do not indicate a mitigation opportunity

At the beginning of roasting, the AA formation starts rapidly. After reaching a maximum within the first half of the total roast cycle, the AA level decreases with continued roasting. Final finished product levels are at only 20–30% of the maximum level, with the final concentration being dependent on the target degree of roast and the total roast time. Darker roasting in general and extending the roast time by using lower roasting temperatures, tends to reduce the AA level but both parameters need to be fixed in narrow ranges to achieve the target flavour profile.

Trials on new and alternative roasting technologies have been conducted. Using a steam/pressure roasting pilot plant unit resulted in a reduction potential of up to 10% in comparison with conventionally roasted sample of similar quality – not indicative of a significant mitigation opportunity.

Other considerations

Results on coffee have led to the conclusion that only very limited process options are available to reduce the AA level without affecting the quality and consumer acceptance of the product.

Processing: Pre-treatment

Development

▶ Pre-drying of green beans and decaffeination have no significant impact on AA

Pre-drying of green beans

Green coffee dried to lower moisture content prior to roasting (from typical green coffee moisture of 10–12% to approximately 7%) did not show an impact on AA level in the roasted product.

Decaffeination

Trials showed that roasting of decaffeinated green coffee beans (covering the commercially important decaffeination processes) resulted in AA levels of the same magnitude as roasting of corresponding untreated coffees when roasted to comparable roasting endpoints.

Processing: Finished product colour

Commercial application

▶ Colour is an important process control point and linked to the sensory properties of the product

Colour is an important indicator of roasting degree and is directly related to the organoleptic properties of the product. Darker roast coffees have less AA than light roast coffees (see section **Processing: thermal input and moisture control** for more details).

Other considerations

Roasting to darker colour is not considered an option to relatively lower AA due to the importance of the sensory attributes of the product. Additionally, the effects of process changes on levels of desirable constituents, e.g. polyphenols and melanoidins, and formation of other undesirable products under extreme roasting conditions, need to be considered.

Processing: Texture/flavour

General considerations

Organoleptic properties are finely tuned by careful selection of green coffee blends, roasting conditions, and processing technologies. Flavour and aroma are crucial to the identity of the products, and any blend/technology changes – however minor – to the existing products will have major impact on the organoleptic properties and subsequently on consumer acceptance.

Final preparation: Consumer and restaurant guidance

When preparing coffee for consumption, whether at home or in restaurants, most common brewing methods effectively transfer AA from roasted coffee beans or soluble coffee into the beverage. The resulting concentrations of AA in both roast and soluble coffees are typically similar, with standard recipes using about 5–7 grams of roast coffee or approximately 2 grams of soluble coffee per cup. Notably, espresso preparation may yield lower levels of AA transfer due to its unique extraction process.

General considerations

The coffee sector remains committed to consumer safety and continues to investigate AA. However, despite ongoing research, FBOs have not targeted any additional mitigation measures since the 2019 toolbox that can be applied to roasted coffee production at an industrial scale. As a result, the coffee sector continues to adhere to the conclusions from the last edition of the Acrylamide Toolbox 2019.

Additionally, when considering potential strategies to reduce AA in coffee, it is crucial to recognise the complex nature of coffee and the potential interplay with other contaminants, such as furan.



Coffee substitutes

(Mainly based on cereals or chicory)



Agronomy: Reducing sugars

Development

- No correlation to AA formation

Coffee substitutes mainly based on cereals

Sugar levels in the cereals (e.g. barley) show no correlation to the amount of AA formed during roasting.

Coffee substitutes mainly based on chicory

Sugar levels in chicory show no correlation to the amount of AA formation during roasting.

Agronomy: Asparagine

Development

- No mitigation options through crop selection due to narrow window of free Asn. Contribution of marginal pathways not yet clarified
- Agronomic aspects not adequately studied and are considered long-term

Coffee substitutes mainly based on cereals

The amount of Asn in cereal (e.g. barley) is relatively low (about 30 mg/100g) and will determine the final amount of AA in the roasted cereal product.

Coffee substitutes mainly based on chicory

The range of free Asn in chicory roots is relatively narrow (40–230 mg/100g). Studies at pilot scale show that Asn content of dried chicory is correlated to the formation of AA.

Other considerations

Other marginal pathways not related to free Asn may become important for the formation of AA.

Recipe: Other minor ingredients

Research

- Calcium and magnesium salts are not effective in reducing AA in coffee
- Adding calcium or magnesium has been evaluated not to be a tool to reduce AA level in chicory

Coffee substitutes mainly based on chicory

Results from laboratory studies showed a significant reduction in roasted chicory AA levels after soaking for two hours in a calcium and/or magnesium ions bath. It resulted in 40–95% lower AA levels, depending on the salts and their concentrations, compared with untreated chicory roasted under similar conditions (temperature and colour).

Although these preliminary results are promising, these considerations have to be included:

- The treatment shows a very significant impact on sensory properties.
- Scaling up trials evidenced significant food safety and environmental concerns.

Recipe: Dilution and piece size

Commercial application

- Recipe modification to accommodate lower percentage of high AA-forming constituents

Coffee substitutes mainly based on chicory

Lowering the chicory content by e.g. 3% in the recipes for coffee substitutes and partial substitution with e.g. roasted barley or chicory fibres achieves reduction, but has an impact on organoleptic properties.

Processing: Asparaginase

Research

- Application of asparaginase enzyme treatment for coffee substitutes (mainly based on cereals or chicory) is limited

Coffee substitutes mainly based on cereals

The applicability of asparaginase enzyme treatment of the cereal grain prior to roasting is limited because roasted cereal products are based on the intact grain. In general terms, exposing intact cereal to asparaginase does not appear to measurably reduce AA levels in the finished product.

Coffee substitutes mainly based on chicory

Laboratory scale trials reveal up to 70% reduction in AA in raw chicory when treated for several hours in an asparaginase solution at appropriate temperature. However, this treatment has a significant impact on final product quality and food safety.

Asparaginase may be provided by the use of enzyme preparations or non-GM baker's yeast containing asparaginase enzyme activity.

Processing: Amidase

Development

- Application of amidase enzymes in coffee surrogates

Preliminary evidence suggests amidase potential to effectively reduce AA levels in coffee surrogates, but further case-by-case testing is required to assess its broader applicability. It is important to note that amidase potential is limited to soluble coffee/coffee surrogates and does not apply to roasted coffee.

Regarding technical aspects, compatibility with existing production processes shall be considered to determine amidase suitability for broader use. Further consideration should be given to the enzyme's performance throughout the entire shelf life of target products and organic product restrictions also need to be considered.

Processing: Thermal input and moisture

Development

- Roasting technologies beyond existing ones have been tested but do not indicate a mitigation opportunity

Coffee substitutes mainly based on cereals

In cereals (e.g. barley) AA is formed at temperatures above 120°C, with a maximum at 150°C. Above 150°C, the AA level decreases with continued roasting. Final finished product levels are at only 30–40% of the maximum level, with the final concentration being dependent on the target degree of roast. Darker roasting in general tends to reduce the AA level but this parameter needs to be fixed in narrow ranges to achieve the target flavour profile.

Coffee substitutes mainly based on chicory

In chicory, AA is formed at temperatures >130°C, with a maximum at 145°C. Above 150°C, rapid decrease of AA begins, and colour development starts due to caramelisation (degradation of sucrose). Decreasing the roasting temperature and concomitantly increasing the roasting time favours the loss of AA. Possible mitigation therefore involves over-roasting (by increasing temperature above 150°C and/or roasting time). This strong heat treatment has a significant impact on the final product's quality (colour development, change of taste) and on its acceptance by the consumer (especially regarding traditional products such as roasted chicory or chicory and coffee mix).

Processing: Pre-treatment

Development

- Soaking of cereal prior to roasting has no significant impact on AA generation

Coffee substitutes mainly based on cereals

Soaking is a common process applied to cereal prior to roasting. However, soaking has no significant impact on AA generation.

Processing: Finished product colour

Commercial application

- Colour is an important process control point and linked to the sensory properties of the product

Coffee substitutes mainly based on cereals

Colour is an important indicator of roasting degree and directly related to the organoleptic properties of the product (see section **Processing: thermal input and moisture** for more details).

Coffee substitutes mainly based on chicory

Colour development results mainly from caramelisation of sugars, and colour is an important endpoint of roasting degree and attribute for consumer acceptance (see section **Processing: thermal input and moisture** for more details).

Processing: Texture/flavour

General considerations

Organoleptic properties of coffee substitutes (mainly based on cereal or chicory) depend on roasting conditions, processing technologies and recipe. The resulting flavour and aroma are essential to the identity of the products and any changes to the existing products (whether process or recipe) may have significant impact on consumer acceptance.



Baby biscuits, infant cereals and baby foods other than cereal-based foods



Product description

According to Regulation (EU) 609/2013, processed cereal-based foods and baby foods for infants and young children comprise:

a. Processed cereal-based foods, which are divided into the following four categories:

- Simple cereals which are or have to be reconstituted with milk or other appropriate nutritious liquids
- Cereals with added high-protein food which are or have to be reconstituted with water or other protein-free liquid
- Pastas which are to be used after cooking in boiling water or other appropriate liquids
- Rusks and biscuits which are to be used either directly, or after pulverisation, with the addition of water, milk or other suitable liquids

b. Baby foods other than processed cereal-based foods.

Recipe: Other minor ingredients

Commercial application

▶ In certain technologies, avoid adding ingredients that may contribute to increasing reducing sugars in the recipe

Infant cereals

In wholegrain, roller-dried infant cereals, the addition of reducing sugars to the mix (e.g. honey, fructose and ingredients dried in a separate process, such as fruit/vegetable/cereal flakes), leads to a higher amount of AA in the final product.

Commercial application

▶ Recipe may impact AA in jarred baby foods

Baby foods other than cereal-based foods

Products containing potato, sweet potato, pumpkin, carrot, prunes/plums and cocoa are at greater risk of higher AA levels, due to relatively higher amounts of AA precursors.

Use of ingredients that have been heat treated, such as fruit purees, vegetable purees (e.g. sweet/regular potato, pumpkin, carrot, etc.) lead to higher total content of AA.

▶ Recipe has a major impact on final AA level

Baby biscuits and cereal-based snacks intended for young children

Generally applicable to wholegrain biscuits, reducing sugars in the recipe may lead to higher amounts of AA in the final product.

Milk as an ingredient is another recipe factor for wholegrain and regular biscuits which may contribute to higher amounts of AA due to the presence of different amino acids and free sugars. Additionally, ammonium carbonate as a leavening agent also has the effect of increasing final AA levels.

Important considerations

Any changes (lowering) of thermal input to reduce AA in baby foods must be carefully considered due to (more severe) microbiological risks.

Processing: Asparaginase

Commercial application

- Asparaginase is very effective in certain infant cereal processes and is applied commercially

Infant cereals

Different technologies are employed to manufacture infant cereals, e.g. extrusion and roller drying. Most ingredients contain a large proportion of cereal flours, and recipes are usually characterised by high water content in the wet mix hydrolysis step, enabling the use of asparaginase. Provided the incubation/residence time, temperature, and mixing conditions are controlled, asparaginase addition can result in a significant decrease (up to 80%) of Asn.

Development

- Asparaginase can be effective in baby biscuits

Baby biscuits

Depending on the technology, and provided the incubation/residence time, temperature, and mixing conditions are controlled, a reduction of AA up to 80% can be observed.

Asparaginase may be provided by the use of enzyme preparations or non-GM baker's yeast containing asparaginase enzyme activity.

Processing: Thermal input and moisture

Commercial application

- Optimisation of thermal input and moisture results in a reduction of AA in baby foods containing prunes

Baby foods, other than processed cereal-based foods, containing prunes

Substantial amounts of AA can be generated at temperatures lower than 100°C under conditions that resemble the drying of foods, such as plums. It is probable that prolonged boiling and/or pasteurisation are responsible for the observed increase in AA.

Modification of the processing and manufacturing conditions under which prunes and prune puree are prepared controls AA formation in the finished product. Cooking under wet conditions at 120°C for one hour shows less formation of AA depending on the variation in Asn content in the raw fruit, recipe and pH of the product.

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