Brussels, 2nd July 2017

Acrylamide Mitigation Strategies: EuCheMS position and proposal

RATIONALE

Acrylamide (ACR) in food is a safety concern (EFSA Journal 2015;13(6):4104 [321 pp.] The Maillard Reaction (MR) is the main pathway for ACR formation: important factors are the presence of its precursors in raw materials (free asparagine and reducing sugar such as glucose and fructose) and the magnitude of the heat load applied during food production (time - temperature combination). The results of ACR concentrations in food coming from EFSA monitoring in 2007-2009 showed mean values of 257-265 µg/kg in home cooked potato products, 219-233 µg/kg in crispbread and 128-140 µg/kg in biscuits. This data together with other minor sources led to a calculated exposure of 1 µg/kg BW per day that created serious concerns, particularly for children.

Mitigation strategies and FCD EuCheMS Position

Over the past 10 years several strategies to reduce ACR concentration in processed food were developed. ACR is formed through the same MR pathway, which contributes to the desired color, flavor, and texture attributes of the final product. Most of the proposed mitigation strategies bring about changes in organoleptic properties of food and dramatically affect the final quality of the product and consequently the consumer's acceptance. The use of asparaginase enzyme, salts and additives as well as the change of time-temperature parameters can dramatically reduce ACR in some foods, as reported in many paper published in literature. Moreover, despite the large availability of methods useful to reduce ACR in foods, in some case (and in some foods) the levels of ACR recovered in 2016 are very similar to those recovered in 2009-2012. Moreover, beside the "high risk" ACR foods (like potato chips or French fries) some foods were poorly investigated in the past (e.g. cocoa and derived products; roasted nuts) and the research could be directed on this in the next future.
EuCheMS supports all the EU Actions finalized to disseminate official rules-guidelines correlated to the mitigation of ACR in foods, particularly for potato-derived foods and foods for children's. Some specific technical data are reported in the **Annex 1, Annex 2, and Annex 3** attached to this Document.

About the authors

EuCheMS, the European Association for Chemical and Molecular Sciences, coordinates the work of 47 Chemical Societies and other chemistry related organisations, representing more than 160,000 chemists. Through the promotion of chemistry and by providing expert and scientific advice, EuCheMS aims to take part in solving today´s major societal challenges.
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Annex 1

Relevant extracts from annexes 2 and 3

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Since the discovery of ACR in foods in 2002, its reduction is a hot topic for the scientific, industrial and institutional communities. In September 2014, EFSA published an infographic about ACR in order to increase public awareness about the topic: it explains how and in which foods ACR is formed, and it lists the basic recommendations of the national authorities to reduce ACR exposure.
In 2013, FoodDrinkEurope published the latest version of Acrylamide Toolbox to provide national and local authorities, manufacturers (including small and medium size enterprises) and other relevant bodies, with brief descriptions of intervention steps which may prevent and reduce formation of ACR in specific manufacturing processes and products.

The three key parameters (KP) related to the introduction of a mitigation strategy aimed at the reduction of a contaminant concentration in food, in this case ACR are.

- KP1 Reduction rate: i.e. the percentage of acrylamide concentration reduction that can be achieved with the specific mitigation strategy respect to the control
- KP2 Side effects: modification of flavour, taste, colour, texture overall liking by consumer, formation of other hazardous compounds connected to the adoption of the specific mitigation strategy
- KP3 Applicability and economic impact: implementation in the industry process and the cost in use of the specific mitigation strategy

Any strategy will deal well with one KP and less with the others but it is important that it is at least sufficient in all of them to be effectively used. The case of coffee where no strategies are sufficiently good for KP2 is a good example . Following some examples of suggestions.

BAKERY
The use of asparaginase as a very effective mitigation strategy in bakeries. No direct influence on product quality was visible and no alterations in organoleptic properties were reported. Bakery products significantly differ in their formulations and processes and the asparaginase activity might be affected from these differences causing variations in the final mitigation level. In particular, enzyme concentration and incubation time can impact on mitigation efficacy. Despite these limitations the application of asparaginase in the different products could be easily implemented and it can be especially useful for products requiring a long resting or leavening time. An important restriction of using asparaginase is the cost of the enzyme: however, some experts pointed out that because of increasing usage the price already decreased in the last two years and it can still drop significantly.
Use an appropriate amount of sulphur in the fertilization plan was considered as a very suitable mitigation strategy. Sulphur-deprived soils can cause an increase in the concentrations of free amino acids such as asparagine, which then can favour ACR formation at high cooking temperatures:
Baking at a lower temperature for a longer time and replacing ammonium bicarbonate with other raising agents are very suitable strategies but negative impact on sensorial and/or nutritional features
Avoiding the use of wholemeal flour is also considered a mitigation strategy although it is somehow conflicting with dietary guidelines promoting the consumption of whole grains linked to the need to increase the dietary fibre intake.
In ranking mitigation strategies for bakeries, adding calcium salt and replacing fructose with glucose were considered the least preferred mitigation strategies

POTATO
The selection of low sugar varieties is the most suitable mitigation strategy in potato sector. Selection of low-sugar varieties is effective, does not have great sensory impact (only moderate impact on colour in same cases) and it is relatively easy to manage in the industry environment, contrary to home preparation.
Also two other strategies aimed at reducing the concentration of sugars i.e. blanching and storing potatoes in controlled conditions were positively considered by the experts highlighting that this is the most effective point to tackle ACR mitigation in potato products.
Similarly, storing potatoes at temperatures above 8°C is a common practice in industry and it is very easy to implement without additional cost. Appropriate storage conditions of potato tubers allowed the keep a low concentration of reducing sugars.
About the mitigation strategies related to the control of oil temperature during frying and the size of the potato pieces this s considered altogether of moderate effectiveness.

In the rank of ACR mitigation strategies for potatoes, suppressing sprouting and adding disodium diphosphate salt were considered the least appropriate mitigation strategies

COFFEE

There are not effective measures to reduce acrylamide concentration in coffee. Dark roasting is effective as well as various treatments that favour the volatilization of acrylamide. However in all cases these strategies will completely change the coffee sensory profile and it would be not acceptable for consumers

Table 1 Literature review about relevant papers supporting each mitigation strategy in bakery sector

Mitigation strategy	Mitigation effect	Experimental parameters	Reference (see Annex2)	Side effect
Add calcium salt	Up to **60%** reduction	Biscuits with calcium chloride 1.0%	47	
	1.5 time reduction (from 110 to 70 µg/kg)	Dough model system with $CaCl_2$ 0.2M	48	
	30% reduction	Calcium salt in wheat bread	49	
	64% reduction	Calcium salt in unsweetened biscuits	49	
	Prevent acrylamide formation **completely**	Model system asparagines and sugar with Ca^{2+}	50	
	1.5 times reduction (from 200 to 130 µg/kg)	Calcium salt in biscuits	24	
	5 times reduction (from 128 ng/g to 24 ng/g)	Addition of 1.0% of Puracal Act 100 (calcium derivate) in biscuits	25	
	1 time reduction (from 2200 to 1950 µg/kg)	Increase NaCl concentration from 1% to 2% in bread rolls	28	
Avoid cereal cultivation in sulphur-deprived soils	Reduction up to **33 times** (from 3124 to 94 µg/kg)	Increasing sulphur fertilization from 30 to 90 mg in pot cultivation Wheat heating heated (30 min at 170°C)	14	Negative impact on flavour [15] Difficult to control the whole production chain and agronomic factors

	Increasing up to **6 times** in flour from sulfur-deficient cultivation	Wheat heating heated (20 min at 180°C)	15	
Avoid wholemeal flour	103.98 µg/kg in whole-wheat flours samples and 12.69 µg/kg in white flours samples (**1.1 time** reduction)	Bread crisp	20	
	188 ug/kg in white wheat bread crust comparing to 390 ug/kg in wheat-wholemeal oat bread crust (**2 times** reduction)	Wheat-wholemeal oat bread	21	
	361.88 µg/kg in white flours samples and 540 µg/kg in cookies replacing 7.5% of flour with fiber (**1.5 time** increase)	Biscuits (cooking at 200°C for 14 min)	51	
Baking at a lower temperature for a longer time	**More than 7 times** reduction (from 690 to less than 100 mg/kg) lowering cooking temperature from 220 at 260°C	Bread rolls cooked for 80 min	28	
	Cooking at 160°C (26 min) prevents acrylamide formation **completely**	Bread crisp	16	
	2 times reduction (from 200 to less than 100 µg/kg) lowering cooking temperature from 200 at 180°C	Biscuits	24	

	Combining partial baking at 220 °C for 2-4 min under conventional conditions with vacuum post-baking at 180 °C and 500 mbar for 4-6 min until the desired final moisture content attained produce **no acrylamide**	Biscuits	17	
Replace ammonium bicarbonate with other raising agents	Reduction from 1200 µg/kg to 70 µg/kg (~ **17 times**)	Substitution of NH_4HCO_3 for $NaHCO_3$ in gingerbread (cooking 5 min a 250°C)	12	Possible alkaline taste [18] Increase in sodium intake [19] Negative but acceptable impact on colour, texture, softness, delicacy [12]
	4 times reduction (from 250 to 60 µg/kg) in cookies with $Na_4P_2O_7$ **6 times** reduction (from 250 to 40 µg/kg) in cookies with Na_4HCO_3	Cookies baked at 205° for 15 min	11	
	4 times reduction (from 180 to 45µg/kg)	Complete replacement of NH_4HCO_3 by $NaHCO_3$ in biscuits (cooking for 5 min a 230°C)	52	
Replace fructose with glucose	Minimal effect	Model dough system	22	
	8 times reduction (from 103.98 to 12.69 µg/kg)	Model dough systems (20 min at 180°C)	49	
	Ambiguous effect	Model sugars/Asn system	30	
Use asparaginase	Range reduction **from 23 to 75 %** depending mainly on pH value of dough and time of enzyme incubation	Cookies baked at 205° for 15 min	11	

84% reduction up to 58 µg/kg in treated biscuits	Asparaginase from *Aspergillus oryzae* in semisweet biscuits (cooking for 5.5 min at 260°C)	53
85% reduction	Asparaginase from *E.coli* in crakers	54
Up to **70%** (depending on enzyme concentration and incubation time and temperature)	Biscuits	13
Up to **97%** reduction (depending on enzyme concentration and incubation time)	Ginger bread (cooking 5 min at 250°C)	12
40% decrease (from 357 to 210 µg/kg)	Wheat-wholemeal oat fermented bread (500 U asparaginase per loaf)	21
Up to **88%** reduction	Whole-wheat bread crisp (2000U asparaginase/ kg of flour)	20
2 times reduction with 210 ASNU asparaginase/kg flour **2 times** reduction with 525 ASNU asparaginase/kg flour **11 times** reduction with 1050 ASNU asparaginase/kg flour	Semisweet biscuit	55

Table 2 Literature review about relevant papers supporting each mitigation strategy in potato products

Mitigation strategy	**Mitigation effect**	**Experimental parameters**	**Reference (see Annex 2)**	**Side effect**
Add disodium diphosphate	**7 times** reduction (from 452 to 58 ng/g)	Fried sweet potatoes (5 min a 165°C) after soaking in 0.5% sodium acid pyrophosphate	56	Possible sensory defects occurring as a result of acrylamide-lowering additives such as citric acid, could in some cases be covered up using flavourings [33]
Blanching	**5 times** reduction (from 750 to 150 µg/kg) in potatoes fried at 150°C **2 times** reduction (from 1700 to 800 µg/kg) in potatoes fried at 200°C	Blanching in hot water at 85°C for 3.5 min	57	Blanching reduces the integrity of the potato [34] The use of $CaCl_2$ may improve product texture, but oppositely can cause a bitter aftertaste [35] Continuous replacement of the blanching water with fresh water is however not feasible, both from environmental and economical point of view [32] Loss of starch and consequent increased oil absorption, shrinkage of raw product leading to decreased recovery in finished product and higher input costs, and changes in finished product texture and taste [33]
	15 times reduction (from 589 to 40 µg/kg)	Potatoes fried at 150°C after blanching in 0.1M $CaCl_2$ solution	50	
	65% reduction	French fries after blanching (70°C, 10–15 min)	33	
	Up to **73%** reduction (depending on patato cultivar and storing time)	French fries after blanching at 80°C for 3 min	58	
	1,4 times reduction (from 3220 to 2220 µg/kg)	Domestic frying after 4.5 min soaking	59	
	54% reduction	Potato chips after 17 min blanching at 64°C	60	
	1.3 times reduction (from 2.1 to 1.6 µg/kg)	French fries after 30 min blanching	61	

	Up to **4 times** (from 600 to 150 µg/kg) depending on treatment time	Microwave-blanching	62	
Cut thicker	**1.5 time** reduction (from 1500 to 1000 ppb) increasing cut size from 8.5x8.5 mm to 10x10 mm	French fries	41	Leading to slower heating [41]
	1.5 time reduction (from 1500 to 1000 ppb) increasing cut size from 8.5x8.5 mm to 10x10 mm	French fries	43	
	5 time reduction (from 12000 to 2500 ppb) increasing slide size from 3 mm to 15 mm	Fried potato slices	43	
Frying at max 175°C	**2 times** reduction (from 750 to 1700 µg/Kg) lowering temperature from 200°C to 150°C	French fries	57	Increasing frying time causes enhancing fat uptake [40] Potato will become soft [39]
	5 times reduction (from 12000 to 2500 µg/Kg) lowering temperature from 167°C (500 sec) to 119°C (2500 sec)	Fried potato power until colour development is still good	63	
	42 times reduction (from 147 to 3.46 µg/Kg) lowering temperature from 185°C (10 sec) to 125°C (60 sec)	Model system: potato power in hot oil	38	

	2 times reduction (from 2500 to 1250 µg/Kg) lowering temperature from 220°C (8 min) to 160°C (20 min)	Fried potato slices	44	
	2 times reduction (from 4439 to 1544 µg/Kg) lowering temperature from 185°C to 175°C	Potato crisps	64	
	1.8 times reduction (from 761 to 401 µg/Kg) lowering temperature from 190°C to 170°C	French fries	65	
	3.1 times reduction (from 761 to 243 µg/Kg) lowering temperature from 190°C to 150°C			
Select low sugar varieties	Variability from 104 to 296 µg/kg (**2.8 times**)	Fried potatoes from 16 different varieties (5 min at 180°C)	66	Only a few of selected cultivar have acceptable sensory and nutritional quality [39]
	Variability from 1660 to 7110 µg/kg (**4.3 times**)	Fried potatoes from 10 different varieties (7.5 min at 140°C)	67	Difficult to control the whole production chain and agronomic factors
	Variability from to 40 to 880 µg/kg (**22 times**)	Fried potatoes (at 175°C for 150 s) from 10 different varieties	10	
	Variability from 230 to 650 µg/kg (**2.8 times**)	Fried potatoes from 4 different varieties (5 min at 180°C)	68	
Store potatoes in controlled conditions	**10 times** reduction (from 2000 to 200 µg/kg) storing potatoes at 8°C and not at 4°C	Fried potatoes from 22 weeks old tubers	66	At lower preservation temperatures, sprouting can be inhibited without the use of

	6 times reduction (from 5000 to 800 µg/kg) storing potatoes at 8°C and not at 4°C	Fried potatoes from 24 weeks old tubers	64	chemicals and the potatoes are less susceptible to diseases
	2 times reduction (from 4000 to 1900 µg/kg) storing potatoes at 8°C and not at 4°C	Crisp from 18 weeks old tubers	64	
	2.5 times reduction (from 12500 to 5000 µg/kg) controlling atmosphere composition (9% O_2 -12% CO_2 vs 18%O_2 3% CO_2)	Fried potatoes from 24 weeks old tubers	69	
Suppress sprouting	**1.7 time** reduction (from 415 to 242 µg/kg) using CIPC	Fried potatoes (2 min at 180°C)	66	Chemical sprout suppressing is not always an option due to customer demand [32]

Annex 2

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(please see following pages)

Annex 3

Supplemental Information

http://www.rsc.org/suppdata/c5/fo/c5fo00655d/c5fo00655d1.pdf

(please see following pages)

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Acrylamide mitigation strategies: critical appraisal of the FoodDrinkEurope toolbox†

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FoodDrinkEurope Federation recently released the latest version of the Acrylamide Toolbox to support manufacturers in acrylamide reduction activities giving indication about the possible mitigation strategies. The Toolbox is intended for small and medium size enterprises with limited R&D resources, however no comments about the pro and cons of the different measures were provided to advise the potential users. Experts of the field are aware that not all the strategies proposed have equal value in terms of efficacy and cost/benefit ratio. This consideration prompted us to provide a qualitative science-based ranking of the mitigation strategies proposed in the acrylamide Toolbox, focusing on bakery and fried potato products. Five authors from different geographical areas having a publication record on acrylamide mitigation strategies worked independently ranking the efficacy of the acrylamide mitigation strategies taking into account three key parameters: (i) reduction rate; (ii) side effects; and (iii) applicability and economic impact. On the basis of their own experience and considering selected literature of the last ten years, the authors scored for each key parameter the acrylamide mitigation strategies proposed in the Toolbox. As expected, all strategies selected in the Toolbox turned out to be useful, however, not at the same level. The use of enzyme asparaginase and the selection of low sugar varieties were considered the best mitigation strategies in bakery and in potato products, respectively. According to authors' opinion most of the other mitigation strategies, although effective, either have relevant side effects on the sensory profile of the products, or they are not easy to implement in industrial production. The final outcome was a science based commented ranking which can enrich the acrylamide Toolbox supporting individual manufacturer in taking the best actions to reduce the acrylamide content in their specific production context.

Introduction

Acrylamide (ACR) is formed in many foods that have undergone heat treatments. Due to its genotoxicity and carcinogenicity, ACR was classified as a Group 2A carcinogen by the International Agency for Research on Cancer[1] and a Category 2 carcinogen and Category 2 mutagen by the European Union;[2] its formation in foods caused worldwide concern.[3]

ACR typically occurs in plant-derived, carbohydrate-rich, heat-treated products. The highest ACR levels have been found in fried and baked potatoes, bread and bakery products and coffee powder.[4] The results of ACR concentrations in food taken from EFSA monitoring in 2007–2009 showed mean values of 257–265 μg kg^{-1} in home cooked potato products, 219–233 μg kg^{-1} in crispbread and 128–140 μg kg^{-1} in biscuits.[5] This data together with other minor sources led to a calculated exposure of 1 μg per kg BW per day that created serious concerns, particularly for children.

The Maillard reaction is the main pathway for ACR formation: important factors are the presence of its precursors in raw materials (free asparagine and reducing sugar such as glucose and fructose) and the magnitude of the heat load applied during food production (time–temperature combination).[6] Varieties selection as well as environmental conditions are known to modify the concentration of ACR precursors; additionally, the processing conditions and the water activity of foods may also play a key role.[7]

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Over the past 10 years several strategies to reduce ACR concentration in processed food were developed. They all have to tackle the main problem: ACR is formed through the same Maillard reaction pathway which contributes to the desired colour, flavour and texture attributes of the final product. Most of the proposed mitigation strategies bring about changes in the organoleptic properties of food and dramatically affect the final quality of the product and consequently the consumer's acceptance.[4]

Since the discovery of ACR in foods in 2002,[8] its reduction is a hot topic for the scientific, industrial and institutional communities. In September 2014, EFSA published an infographic about ACR in order to increase public awareness about the topic: it explains how and in which foods ACR is formed, and it lists the basic recommendations of the national authorities to reduce ACR exposure. In the same period, EFSA provided a scientific opinion about the risks related to acrylamide presence in food: this document included an assessment of the dietary exposure to acrylamide, an evaluation of the toxicological hazards and a characterisation of the risks to human health.[9] Basically, these documents concluded that although there is no conclusive evidence on increased risk for consumer health related to ACR ingestion, mitigation strategies to reduce ACR in food should be pursued.

In 2013, FoodDrinkEurope released the latest version of Acrylamide Toolbox to provide national and local authorities, manufacturers (including small and medium size enterprises) and other relevant bodies, with brief descriptions of intervention steps which may prevent and reduce formation of ACR in specific manufacturing processes and products. In particular, Toolbox is intended to provide individual SME with limited R&D resources, indications about the intervention steps identified so far that may be helpful to reduce acrylamide formation in their specific manufacturing processes and products. To support SMEs in the implementation of the Toolbox, FoodDrinkEurope and the European Commission, Directorate General Health and Consumer Protection, in collaboration with national authorities, developed specific ACR leaflets for five key food sectors (biscuits, bread, breakfast cereals, potato crisps and French fries).

Food science experts acknowledge that not all the proposed strategies have equal value in terms of efficacy, side effects or applicability. The objective of this paper is to enrich and potentiate the Toolbox indications with a science-based commented ranking of the proposed mitigation strategies presented in the Acrylamide Toolbox.

For this purpose we focused on two of the five key sectors described in the acrylamide leaflets namely bakery (including biscuits, bread, and breakfast cereals) and potato products (including crisps and French fries). A specific procedure was designed in order to obtain independent assessment from five authors, than the ranking of the various strategies proposed for ACR mitigation presented in the Toolbox was provided. The use of enzyme asparaginase and the selection of low sugar varieties were scored as the best mitigation strategies in bakery and in potato products, respectively.

Results and discussion

Key parameters (KPs) importance weight

The three key parameters (KPs) selected in this study take into consideration the main aspects related to the introduction of a mitigation strategy aimed at the reduction of a contaminant concentration in food, in this case ACR.

KP1 Reduction rate: *i.e.* the percentage of the contaminant concentration reduction that can be achieved with the specific mitigation strategy with respect to the control

KP2 Side effects: modification of flavour, taste, colour, texture overall liking by consumer, formation of other hazardous compounds connected to the adoption of the specific mitigation strategy

KP3 Applicability and economic impact: implementation in the industry process and the cost in the use of the specific mitigation strategy

Narrative attributes and corresponding predefined values for each KP are summarized in Table 1. All the three KPs are very important and interconnected: if a mitigation strategy does not lead to a significant reduction rate there is no point in applying it. On the other hand, if the final product is not sensorially attractive for the consumer it will not be eaten at all. Finally, if the two first KPs are satisfied, but the strategy is too expensive or not applicable to the specific product or to the specific production plant, it cannot be implemented by the company as the cost of using it becomes too high.

It is clear that in the absence of any regulatory restriction[10] or also a sound nudging policy addressing the importance of reducing ACR concentration, the final decision to implement a specific mitigation strategy in the production process is in the hands of the producers. It can be foreseen that within each company the decision to implement an acrylamide mitigation strategy will only come after a careful consideration of the several trade-offs concerning production costs, sensory product characteristics company policy, brand positioning and marketing considerations.

The design of the study, which is described in detail in the experimental section, was based on a consensus among the authors on the articles that should be considered for this assessment which are listed in Tables 3S and 4S (ref. 10–18, 20–22, 24, 25, 28, 30, 32–35, 38–41, 43, 44 and 48–70).† After this first step there was further discussion among authors about the score and the weight of the three KPs. They worked totally independently without any possibility of influencing each other's opinions or changing their score during manuscript preparation.

As reported in Table 2, the five authors were in good agreement in selecting side effects and applicability and economic impact as the most important parameters, but also in considering all KPs very relevant. No author selected reduction rate as the most important KP, however two of them considered reduction rate and side effect equally important. The score on the weight of the KPs depends on the sensitivity to the different aspect of the problem and likely mirrored the situation of companies willing to introduce acrylamide mitigation strategies in their products.

Table 1 Predefined meaning proposed by the expert for each possible value to be attributed to key parameters

Score	KP1 reduction rate	KP2 side effect	KP3 applicability and economic impact
1	Not effective	Very important side effect	Not applicable at all
2	Moderately effective	Obvious side effect	Applicable with limitations
3	Very effective	Limited side effect	Applicable
4	Decisive	No side effect	Easy to apply

Table 2 Key parameters evaluation: values attributed by each expert

	Reduction rate	Side effect	Applicability and economic impact
Expert 1	2.0	4.0	4.0
Expert 2	2.5	2.5	5.0
Expert 3	3.0	4.0	3.0
Expert 4	3.0	4.0	3.0
Expert 5	3.0	3.0	4.0

Mitigation strategies in bakery products

Table 3 shows the overall score obtained and illustrated by a colour indication highlighting the efficacy according to the authors' indication. In the right column the main consideration to critically assess the opinions of the authors are provided. In many cases, the average values are the final results of relevant differences in the authors' opinions. To keep track of these differences the marks given by each evaluator about the ACR mitigation strategies in bakery products are reported in Table 1S.†

The authors were quite in agreement (4 out of 5) in considering the use of asparaginase as a very effective mitigation strategy in bakeries. The mechanism of asparaginase action is based on the conversion of free asparagine into aspartic acid, which is not a source of acrylamide formation.[11] Asparaginase use was unanimously considered as an effective mitigation strategy so that the scores on KP1 were high. Moreover, no direct influence on product quality was visible and no alterations in organoleptic properties were reported, therefore KP2 also usually scored very high. On the other hand, the evaluation on KP3 was less favourable highlighting the limitations in the applicability of the enzyme treatment in some production processes. Bakery products significantly differ in their formulations and processes and the asparaginase activity might be affected by these differences causing variations in the final mitigation level. In particular, enzyme concentration and incubation time can have an impact on mitigation efficacy.[12,13] Despite these limitations the application of asparaginase in different products could be easily implemented and it can be especially useful for products requiring a long resting or leavening time. An important restriction of using asparaginase is the cost of the enzyme: however, some authors pointed out that because of increasing usage the price of commercially available asparaginases already decreased in the last two years and it can still drop significantly in the near future.

Avoiding cereal cultivation in sulphur-deprived soils (*i.e.* use of an appropriate amount of sulphur in the fertilization plan) was considered as a very suitable mitigation strategy by two of the authors and as a moderately suitable mitigation strategy by the other three. Sulphur-deprived soils can cause an increase in the concentrations of free amino acids such as asparagine[14] which then can favour ACR formation at high cooking temperatures: this effect is quite strong so the authors considered this mitigation strategy effective with high KP1 values. In respect to side effects the negative impact observed on the flavour of biscuits prepared with wheat cultivated in sulphur-rich soils was highlighted: ACR mitigation strategies that cause large changes in the free amino acid composition are likely to lead to significant effects in aromatic volatile compositions (for example in 2-vinylfuran, 2-isopropylpropenal, 1-methylpyrrole, 2-methyl-2-butenal, 3-methylbutanal, 1,3-dimethylpyrrole).[15] Despite this finding, the opinion of some authors was that the sensorial changes determined by agronomic practices will not be so important as to be perceived by consumers and therefore they also gave high KP2 values. Unfortunately, avoiding cereal cultivation in sulphur-deprived soils is a mitigation strategy relatively hard to realize, it is difficult to control because the producers do not have the possibility to control the entire supply chain, *i.e.* all SMEs. Moreover, sulphur fertilization is not applicable for organic production and for this reason some of the authors gave low scores to KP3 of this mitigation strategy.

In ranking the mitigation strategies for bakeries, similar scores were obtained by "baking at a lower temperature for a longer time" and by "replacing ammonium bicarbonate with other raising agents" (two authors considered them very suitable strategies, two moderately suitable and one considered them as not suitable because of the negative impact on sensorial and/or nutritional features). Both strategies obtained high scores for the KP1 (reduction rate), however they were not well scored for KP2 (side effects). The Maillard reaction is a temperature-dependent reaction so baking at a lower temperature for a longer time can have a very strong effect on the reduction of ACR concentration so the KP1 values were very favourable. It has been shown that preparing crispbread at 160 °C for 26 min inhibited completely acrylamide formation. Unfortunately, this mitigation strategy causes important changes in dryness, shelf-life and sensory features so KP2 received low scores.[16] Significant differences in taste, smell, colour and overall sensory scores comparing biscuits baked by using the conventional process and biscuits baked by combined

Table 3 Ranking of mitigation strategies in bakery products: values from each expert. Data were clustered into three groups with different colours representation: final value > 30 = high suitability = green colour; 30 < final value < 25 = moderate suitability = yellow colour; final value < 25 = low suitability = red colour

	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Considerations underlying the score
Use of asparaginase	36.6	30.5	31.3	31.3	22.9	Using asparaginase is a very efficient strategy for products having long resting or leavening time. It combines high ACR reduction rate and low impact on sensorial features. In some products the enzyme has no time to work and thus the application will not be effective. In addition, some bakery formulations do not provide optimal pH conditions for asparaginase action.
Avoid cereal cultivation in sulphur-deprived soils	29.3	27.1	32.1	31.3	29.5	Avoiding the cultivation of cereal in sulphur deprived soil is a very efficient strategy but it is not useful for SMEs not having the possibility to control the origin of raw material in the cereal commodities market. It could represent a nice opportunity for big companies which could implement supply policies on the cereal chain.
Baking at a lower temperature for a longer time	36.6	27.1	27.4	33.3	21.9	Baking at a lower temperature for a longer time could be an efficient strategy but it often influence the sensory characteristics of the product. Bakery production lines are currently optimized keeping into account a particular heat flux and product flow. Re-designing a production line will affect economic parameters of production and will not happen unless a limit of acrylamide concentration is established.
Replace ammonium bicarbonate with other raising agents	24.4	33.9	29.2	30.2	28.6	Replacing ammonium bicarbonate with other raising agents has been proven to be successful in some traditional bakery products with low rise; however in different products it can affect sensory properties. In addition this mitigation strategy increases sodium intake, so it is not advisable from the nutritional point of view.
Avoid wholemeal flour	26.8	23.7	25.5	27.1	32.4	The general nutritional recommendation is to increase the consumption of whole grain and avoid the refined flours. Therefore, although very feasible, avoiding wholemeal flour is not a recommended mitigation strategy.
Add calcium salts	24.4	27.1	32.1	19.8	32.4	Adding calcium salts is a cumbersome mitigation strategy. The conditions in which the salt is added to the dough are critical not only for achieving significant acrylamide reductions but also to get a final product without strong changes in critical sensorial properties such as colour, aroma, and mechanical properties.
Replace fructose with glucose	22.0	30.5	22.6	27.1	32.4	Replacing fructose with glucose is not an applicable mitigation strategy for diabetic products where fructose is preferred.

processes using vacuum and lower temperature were also reported.[17] In addition, from an industrial point of view, slower cooking negatively influences the effectiveness of the process so manufacturers are not always willing to accept it therefore KP3 also got low scores by some evaluators – authors. Baking lines are designed and engineered keeping in mind specific heat flux and product flow: if the heat flux is going to change, this will affect product flow and will have an impact on the economic parameters of production.

Raising agents different from ammonium bicarbonate produce a significant reduction in ACR formation: other inorganic salts modify the pH value of matrices, thus reducing ACR formation.[11] In fact, a high reduction rate was reported in the literature. For instance a reduction of up to 17 times was found in gingerbread substituting NH_4HCO_3 for $NaHCO_3$. Consequently, the KP1 of this mitigation strategy was scored relatively high by the five authors. In addition, the replacement of the raising agent did not have a great impact on production processes (in terms of management or cost) so this mitigation strategy was considered easy to apply with high KP3 values. On the other hand, raising agents different from ammonium bicarbonate can cause marked changes in sensorial attributes of the final products. This was observed in gingerbread and shortbread manufactured with $NaHCO_3$ showing altered colour, texture, softness, delicacy.[12,18] Moreover, the use of sodium bicarbonate has an important nutritional pitfall as it leads to the increase of sodium intake.[19]

Avoiding the use of wholemeal flour is also proposed in the acrylamide toolbox as a possible mitigation strategy. However, this strategy is somehow conflicting with dietary guidelines promoting the consumption of whole grains linked to the need to increase the dietary fibre intake. Three authors evaluated it as a moderate suitable strategy, one as a very suitable strategy and one not enough suitable. Use of wholemeal flour brings more asparagine to the bakery formulation, which in turn increases ACR formation upon baking.[20] However, avoiding wholemeal flour could only moderately decrease ACR formation and this resulted in low KP1 scores: no more than two times reduction was reported in wheat-wholemeal oat bread.[21] Although very feasible this strategy caused the loss of the sensory properties desired by those consumers who like the whole wheat products: in this respect the authors gave good values to KP3 but the marks of KP2 was also not very favourable.

In ranking the mitigation strategies for bakeries, adding calcium salt and replacing fructose with glucose were considered the least preferred mitigation strategies (two authors scored them high, one moderate and two low).

The impact of calcium salt is moderate and potential side effects are often clearly perceived, therefore both KP1 and KP2 were scored low by most of the authors. Several studies indicated that polyvalent cations reduce ACR formation in thermally processed snack foods and bakery products.[22,23] Unfortunately this mitigation strategy is not as simple as it appears at first glance: salt, particularly calcium salts, should be added to the dough in specific conditions to reach satisfactory percentages of reductions and to get a final product without strong changes in critical qualitative properties: increasing lightness parameter and decreasing redness were reported as effects of calcium salt in cookies,[24–27] In addition, higher sodium chloride concentrations could increase the ACR level[28] and the presence of salts increases the rate of sugar decomposition leading to the formation of a high amount of hydroxymethylfurfural (HMF). From an industrial point of view, adding calcium salt has been considered simple and economic so some authors evaluated this as an applicable mitigation strategy (high KP3 value). However, in some specific operative conditions the use of this salt becomes cumbersome because of the limited solubility of $CaCl_2$. Considering this evidence some authors also scored this mitigation strategy low for KP3.

It has been suggested that the formation of a key intermediate from sugars which goes on to react with asparagine occurs *via* a single step for fructose and *via* multiple steps for glucose so replacing fructose with glucose can reduce the ACR final content in bakeries.[29] This is a very simple mitigation strategy and most of the authors evaluated it applicable with high KP3 values. On the other hand, it obtained very low KP1 values because replacing fructose with glucose leads only to a minor improvement in terms of the mitigation achieved for most of the bakery products.[26,30] Additionally, KP2 was scored low because of the possible side effects on colour features.

Mitigation strategies in potato products

A summary of the authors evaluation about ACR mitigation strategies in potato products is reported in Table 4 while in Table 2S† the details of the scores given by each author on the three KPs for each strategy are listed.

The authors are in good agreement (4 out of 5) in pointing out the selection of low sugar varieties as the most suitable mitigation strategy in the potato sector. Because of the high concentration of free asparagine in the tubers reducing sugars are the limiting reagents during ACR formation in thermally processed potatoes[31] so significant ACR reductions could be obtained by using low reducing sugar potato varieties: reduction rate up to 22 times was reported in fried potatoes.[32] The selection of low-sugar varieties is effective, does not have a great sensory impact (only moderate impact on colour has been reported in some cases) and it is relatively easy to manage also at the SME level, contrary to home preparation. For these reasons, this mitigation strategy was scored well by most of the authors for the three KPs the suitability of some low sugar potato varieties for the preparation of specific potato products being the only concern.

Also two other strategies aimed at reducing the concentration of sugars before processing, *i.e.* blanching and storing potatoes in controlled conditions were positively considered by the authors highlighting that this is the most effective point to tackle ACR mitigation in potato products.

Three authors considered blanching and storing potatoes under controlled conditions as very suitable mitigation strategies in potato products, one evaluated this strategy as moderately effective while one gave it a low score.

This figure is the result of very high marks for KP3: though blanching leads to an increase in the production time, the additional costs were considered acceptable and blanching is a common and feasible practice in the industry. Scores were high also for KP1: blanching is an effective way to leach out not only the reducing sugars but also asparagine leading to the production of fried potatoes having low ACR content. In fact, a reduction rate up to 65% was reported after blanching for French fries made from tubers rich in sugars.[33] The weak point of this strategy is KP2 as the organoleptic properties of the final product could be altered in a different way. The possible side effects are: reduction of potatoes integrity[34] and bitter aftertaste.[35] The extent and severity of these side effects depended on several factors such as time and temperature so the blanching process needs to be tailored to the specific production process in order to be really effective.

Similarly, storing potatoes at temperatures above 8 °C is a common practice in industry and it is very easy to implement this practice without additional cost. Appropriate storage conditions of potato tubers allow us to keep the concentration of reducing sugars low. De Wilde and co-workers[36] observed 10 times ACR reduction in French fries obtained from potatoes stored at 8 °C compared to those stored at 4 °C. So, as observed for the previous mitigation strategy, also in this case high values for KP1 and KP3 were recorded; however also in this case the main problems are related to the side effects (KP2). In fact, the disadvantages are related to the negative impact of long storage at higher temperature on potato quality. Storage at 4 °C inhibited sprouting avoiding the use of chemical products; moreover the growth of moulds and other biological agents is also prevented.

About the mitigation strategies related to the control of oil temperature during frying and the size of the potato pieces, two authors considered frying at max 175 °C and cutting potatoes thicker as very suitable mitigation strategies. Three

Table 4 Ranking of mitigation strategies in potato products: values from each expert. Data were clustered into three groups with different colours representation: final value > 30 = high suitability = green colour; 30 < final value < 25 = moderate suitability = yellow colour; final value < 25 = low suitability = red colour

	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Considerations underlying the score
Select low sugar varieties	35.1	28.2	30.2	30.4	31.3	Significant ACR reductions could be obtained by using low reducing sugar potato varieties. This mitigation strategy is easily manageable also at the SME level. The selection of potato varieties should be combined with product specific other factors (cost, type of product, technological performance) having higher priority than the potential to form acrylamide during processing.
Blanching	26.8	28.2	30.2	30.4	33.3	Blanching is an effective and scalable way to mitigate ACR production in potato products although in some cases the sensorial properties of the final product could be altered. It needs an optimization process about the conditions however it is manageable also in SME without structured R&D.
Store potatoes in controlled conditions	22.7	28.2	34.2	32.5	31.3	Proper storage conditions of potatoes could maintain the proper level of reducing sugars. This is a simple and manageable preventive measure to limit ACR formation in fried products. The main drawback is that it can reduce potato shelf-life and it can have adverse effects on quality.
Fry at max 175 °C	26.8	27.0	31.2	30.4	26.3	Frying at lower temperature is a very effective strategy in acrylamide reduction: unfortunately it affects the final quality. Using lower temperature lack of crispiness in higher moisture products and higher oil content in final products were observed. For caterers and home cooking this mitigation strategy is less effective as people usually fry potatoes till a desired end color.
Cut thicker	28.9	19.6	34.2	31.4	26.3	Geometrical dimension of the pieces to fry is a simple measure easy to apply especially for French fries, but not for potato chips. The main concern is related to consumer expectation: changing the geometry could fail to meet consumer tastes.
Suppress sprouting	28.9	34.4	23.1	25.1	24.2	Sprout suppressants may moderately reduce ACR formation without nutritional or qualitative impacts on the final product. This mitigation strategy is suitable only for big companies and not for SMEs because a specialized equipment is necessary.
Add disodium diphosphate	30.9	34.4	17.1	19.9	27.3	Adding disodium diphosphate is a common and simple mitigation strategy as this salt is also applied to avoid discolouration. On the other hand it could deeply affect sensory properties and it requires very careful optimization of the conditions achievable only in some products. The addition of extra sodium does not meet the nutritional recommendations.

authors scored as moderate the control of oil temperature, two scored as moderate and one scored low the strategy of cutting potato thicker.

ACR formation in potatoes parallels the increase of the temperature,[37,38] so frying at moderate temperature is in principle quite an effective strategy for ACR reduction and it was evaluated with relatively high KP1 scores by the authors. Also in this case, very high marks for KP3 were attributed by the authors but most of them indicated obvious side effects with low KP2 values. The organoleptic properties of the final product could be drastically changed by this approach: in particular, this mitigation strategy may lead to increased absorption of oil in fried potatoes with effect on crispness, moisture, mealiness and colour.[39] As a consequence the nutritional properties in terms of amount of fat absorbed by the fried potatoes also could be affected.[40] For pre-cooked French-fries intended for frying at home or at restaurants, another weak point is the low compliance with the cooking instructions. The Toolbox suggests to provide clear cooking instructions on every pack (fry at max 175 °C, do not overcook, aim for light golden colour), however consumers often do not respect the instruction and this cannot be controlled upstream.

Similar considerations were taken into account by the authors about the geometrical dimensions of the pieces. Cutting potatoes in thicker pieces is a simple measure that can be practically applied. However, the total effect of thickness is moderate due to two opposite facts. As a strip thickness increases, the volume-to-surface area ratio increases, leading to slower heating of the strip during frying. Therefore, for the same frying time, the acrylamide level of the larger potato pieces is expected to be lower. However, because the frying process must be prolonged to allow the cooking of the starch at the core, the overheating of the surface may in turn result in higher ACR levels.[41,42] As a matter of fact, no more than 5 times ACR reduction was observed as an effect of this mitigation strategy.[43] Moreover, this mitigation strategy substantially changes the nature of the product and it strongly reduces the preference of some consumers who like thinner and crispy fries. For this reason, this strategy received moderate score both for KP1 and KP2 and high marks for KP3.

In the ranking of ACR mitigation strategies for potatoes, suppressing sprouting and adding disodium diphosphate salt were considered the least appropriate mitigation strategies by the authors (1 high, 2 moderate, 2 low evaluations and 2 high, 1 moderate, 2 low evaluations, respectively). Sprout suppressants such as Chlorpropham and isopropyl-*N*-(3-chlorophenyl-carbamate) (CIPC) are also able to prevent starch degradation and subsequently the increasing of free glucose during storage.[44] For this reason this is a potentially effective measure: the lower the reducing sugar content, the greater the inhibition of ACR formation. However, the observed effect on ACR reduction is moderate: no more than 1.7 times reduction rate was reported in fried potatoes added with CIPC[45] and for this reason the KP1 scores were not favourable. Additionally, this mitigation strategy was unfavourable also for the KP3 parameter: in fact, it is a measure not easy to apply because specialized equipment is necessary and the use of agrochemicals is not well received by consumers. No nutritional or qualitative impacts of this mitigation strategy have been reported so far, therefore the authors are in agreement pointing out limited side effects (therefore high KP2 values).

Adding disodium diphosphate salt is a common practice in industry to avoid potato discolouration[46] so its application in order to reduce ACR formation is very easy to apply from a technical point of view (quite high KP3 scores). The rationale behind this strategy is that addition of disodium diphosphate salt decreased the pH at the potatoes surface and thus inhibiting ACR formation. However the observed final effects were not that clear (see ref. 57) and therefore the KP1 values assigned by the evaluators – authors were on average rather low. Also evaluations about KP2 led to low scores as this mitigation strategy could generate different side effects if the conditions in which disodium diphosphate is added are not perfectly controlled. In most of the cases, the addition of disodium diphosphate could lead to off flavour and off taste of the product which could lead to consumers rejection.

For each strategy, strengths and weaknesses guiding authors are shown in Table 4.

Experimental

Five scientists from different geographical areas with high expertise in acrylamide mitigation strategies were involved in the experimental procedure of this paper to provide critical evaluation about the ACR mitigation strategies listed in the FoodDrinkEurope ACR toolbox. High knowhow within the working group was guaranteed on the basis of their record of scientific papers of the last 10 years on the subject ACR mitigation strategy and balancing their geographical origin in order to cover different areas and taking into account the different local specific conditions (for example cultivars available, practice in the local companies, national legislation) and issues around the world. The five authors acting as experts were coordinated by the authors working at Wageningen and Naples Universities.

In the first phase the authors contributed to the construction of Tables 3S and 4S provided in the ESI† of this article. These tables were constructed after an extensive survey of the articles published in scientific journals indexed in the Web of Science (all databases) from 2004. The search was performed using keywords such as "acrylamide" and "mitigation" as well as the word "acrylamide" coupled with the names of specific mitigation strategies (*e.g.*, blanching, sulfur or asparaginase). In the second phase considering the information summarized in the tables and on the basis of their own experience the authors gave their evaluations exclusively on the mitigation strategies listed in the Toolbox. No discussion was allowed in this phase as the study design was a survey aimed at catching the sensitivities of scientists in the field having different interests and background and not aimed at the elaboration of a consensus document.

The preliminary phase of the evaluation was related to the relative importance of the various parameters contributing to the efficacy of a mitigation strategy. A similar approach was used in different fields such as habitat suitability studies.[47] The authors had a total of 10 points and they could distribute them within three key parameters (KPs) that are of importance in the evaluation of the overall efficacy of the mitigation strategies proposed in the Toolbox. KP1 effectiveness in the ACR reduction rate; KP2 sensory and nutritional side effects caused by the mitigation strategy with respect to the corresponding conventional product; KP3 applicability and economic impact in the industrial process. In a second step, they gave a value from 1 to 4 to each of the KPs for each mitigation strategy proposed in the Toolbox.

The marks given by each author to each of the mitigation strategy were multiplied for the relative importance weight (s) he gave to the single KP. Finally a normalizing factor was applied in order to equalize the weightage of the five authors to the final results. For this purpose the values were normalized using a coefficient in order to have a total score of 200 points for each author. Therefore the final evaluation of each parameter is:

$$\begin{aligned}\text{Final value} = {} & (\text{value to each key parameter}) \\ & \times (\text{relative importance weight}) \\ & \times (\text{normalization factor}).\end{aligned}$$

A clusterization of final values was performed in order to give a visual representation of the efficacy of each strategy for the specific food chain.

Final value > 30: High efficacy (highlighted in green in the tables)

30 < Final value < 25: Moderate efficacy (highlighted in yellow in the tables)

Final value < 25: Low efficacy (highlighted in red in the tables)

The use of the colored graphical notation and the selection of the intervals were arbitrary and aimed at making more explicit the key message of the paper.

Conclusions

In 2014 FoodDrinkEurope's Acrylamide Toolbox released infographic material to illustrate the available strategies in order to reduce ACR content in food. Strategies were grouped per each food sector to increase the usefulness for the SMEs that wish to implement an ACR mitigation policy. However, experts in the acrylamide field acknowledge that not all the mitigation strategies have equal value in terms of efficacy, side effects or applicability. The commented ranking here developed could enrich the Toolbox indications and better support SMEs in their final decisions about mitigation actions to be used in order to obtain a reduction of ACR concentration in their products.

According to the authors' evaluation of the mitigation strategies in the bakery sector, the use of the enzyme asparaginase resulted in the best way to reduce the ACR content. The caveat that for some products the enzymatic approach is less effective or less feasible than other strategies is considered of minor importance and processing can be adapted easily. The strongest point in the use of the enzyme is the lack of negative impact on product quality as it does not lead to alteration of organoleptic properties. In addition, the use of asparaginase is easy to handle and the relatively high costs will probably decrease in the near future and can be managed with appropriate strategies.

The cultivation in non-sulphur-deprived soils was also positively evaluated for those companies that could control the supply chain, while the other two process strategies (baking at a lower temperature for a longer time and replacing ammonium bicarbonate with other raising agents) had some drawbacks mainly because of the side effects and applicability at the industrial level.

As far as the potato products sector is concerned, all strategies leading to the reduction of free sugar in the product before thermal processing are well considered. In particular, whenever it is possible to select low sugar varieties this allowed a significant ACR reduction without any variations in the production process; moreover blanching and storing potatoes in controlled conditions also scored very high. All these measures showed a good impact on the reduction of final ACR values without a significant economic impact on the production process, although there are still some concerns on the sensory acceptability.

The evaluation process reported in this paper summarized independent opinions of scientists from different geographical areas and background experience also highlights the different sensitivities among academics about the available ACR mitigation strategies in the potato and bakery sectors. In particular, it was noted that the different weightages given to the key parameters (KPs) are strongly dependent on the sensitivity of the single author to factors like industrial applicability or sensory impact of the mitigation strategy. This behaviour exactly replicates the drivers of the decision making procedure occurring in real industrial conditions. It is a useful exercise to verify how the ranking can change if the KP weight is modified without changing the score given to each mitigation strategy. For instance, if we imagine a situation where an acrylamide concentration limit is imposed by the regulatory agency the KP1 factor (reduction rate) becomes much more important than KP2 on the sensory effect and the mitigation strategies based on milder processing conditions would immediately climb to the top of the rank.

In conclusion, it is worth reminding that this is not a consensus document. Although the consulted literature listed in ESI Tables 3S and 4S† was in common, the authors worked independently without discussing their scores with the others and without possibility to change their original evaluation during the following process. For this reason the numerical scores used in order to highlight the results should be considered only as qualitative indications not as quantitative parameters.

Nevertheless the final results showed a common ground for the above recommendations and when the comments to the three KPs are considered separately the considerations made by the authors were well aligned.

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Supplementary material

Table 1S Scores given by each expert on the three KP for each strategy in bakery sector

		Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
KP1	Use asparaginase	3	2.5	3	3	2
	Avoid cereal cultivation in sulphur-deprived soils	2	2	3	3	3
	Baking at a lower temperature for a longer time	3	2	4	4	3
	Replace ammonium bicarbonate with other raising agents	2	2.5	3	3	3
	Avoid wholemeal flour	3	2	2	3	2
	Replace fructose with glucose	1	2	2	2	2
KP2	Use asparaginase	4	2.5	3	4	3
	Avoid cereal cultivation in sulphur-deprived soils	3	2	3	3	4
	Baking at a lower temperature for a longer time	3	2	2	3	2
	Replace ammonium bicarbonate with other raising agents	2	2.5	2	2	3
	Avoid wholemeal flour	2	1	2	2	4
	Replace fructose with glucose	2	3	2	2	4
KP3	Use asparaginase	2	2	3	3	2
	Avoid cereal cultivation in sulphur-deprived soils	2	2	3	4	2
	Baking at a lower temperature for a longer time	3	2	4	2	2
	Replace ammonium bicarbonate with other raising agents	2	2.5	4	4	3
	Avoid wholemeal flour	2	2	4	3	4
	Replace fructose with glucose	2	2	4	3	4

Table 2S Scores given by each expert on the three KP for each strategy in potato sector

		Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
KP1	Select low sugar varieties	3	2.5	3	3	2
	Blanching	3	1	4	3	3
	Store potatoes in controlled conditions	3	2.5	3	3	2
	Fry at max 175°C	3	2.5	3	3	2
	Cut thicker	2	2	2	3	2
	Suppress sprouting	2	3	2	2	2
	Add disodium diphosphate	3	3	3	2	2
KP2	Select low sugar varieties	4	3	2	3	4
	Blanching	2	2.5	2	3	3
	Store potatoes in controlled conditions	2	3	4	3	4
	Fry at max 175°C	2	2.5	2	2	2
	Cut thicker	3	2	3	3	2
	Suppress sprouting	3	3	3	3	3
	Add disodium diphosphate	3	3	1	1	3
KP3	Select low sugar varieties	3	3	4	3	3
	Blanching	3	4	3	3	4
	Store potatoes in controlled conditions	2	3	2	4	3
	Fry at max 175°C	3	3	4	4	4
	Cut thicker	3	2	4	4	4
	Suppress sprouting	3	4	2	2	2
	Add disodium diphosphate	3	4	2	2	3

Table 3S Literature review about relevant papers supporting each mitigation strategy in bakery sector

Mitigation strategy	Mitigation effect	Experimental parameters	Reference	Side effect
Add calcium salt	Up to **60%** reduction	Biscuits with calcium chloride 1.0%	1	
	1.5 time reduction (from 110 to 70 µg/kg)	Dough model system with $CaCl_2$ 0.2M	2	
	30% reduction	Calcium salt in wheat bread	3	
	64% reduction	Calcium salt in unsweetened biscuits	3	
	Prevent acrylamide formation **completely**	Model system asparagines and sugar with Ca^{2+}	4	
	1.5 times reduction (from 200 to 130 µg/kg)	Calcium salt in biscuits	5	
	5 times reduction (from 128 ng/g to 24 ng/g)	Addition of 1.0% of Puracal Act 100 (calcium derivate) in biscuits	6	
	1 time reduction (from 2200 to 1950 µg/kg)	Increase NaCl concentration from 1% to 2% in bread rolls	7	
Avoid cereal cultivation in sulphur-deprived soils	Reduction up to **33 times** (from 3124 to 94 µg/kg)	Increasing sulphur fertilization from 30 to 90 mg in pot cultivation Wheat heating heated (30 min at 170°C)	8	Negative impact on flavour [9] Difficult to control the whole production chain and agronomic factors
	Increasing up to **6 times** in flour from sulfur-deficient cultivation	Wheat heating heated (20 min at 180°C)	9	
Avoid wholemeal flour	103.98 µg/kg in whole-wheat flours samples and 12.69 µg/kg in white flours samples (**1.1 time** reduction)	Bread crisp	10	
	188 ug/kg in white wheat bread crust comparing to 390 ug/kg in wheat-wholemeal oat bread crust (**2 times** reduction)	Wheat-wholemeal oat bread	11	
	361.88 µg/kg in white flours samples and 540 µg/kg in cookies replacing 7.5% of flour with fiber (**1.5 time**	Biscuits (cooking at 200°C for 14 min)	12	

	increase)			
Baking at a lower temperature for a longer time	**More than 7 times** reduction (from 690 to less than 100 mg/kg) lowering cooking temperature from 220 at 260°C	Bread rolls cooked for 80 min	7	
	Cooking at 160°C (26 min) prevents acrylamide formation **completely**	Bread crisp	13	
	2 times reduction (from 200 to less than 100 μg/kg) lowering cooking temperature from 200 at 180°C	Biscuits	5	
	Combining partial baking at 220 °C for 2-4 min under conventional conditions with vacuum post-baking at 180 °C and 500 mbar for 4-6 min until the desired final moisture content attained produce **no acrylamide**	Biscuits	14	
Replace ammonium bicarbonate with other raising agents	Reduction from 1200 μg/kg to 70 μg/kg (~ **17 times**)	Substitution of NH_4HCO_3 for $NaHCO_3$ in gingerbread (cooking 5 min a 250°C)	15	Possible alkaline taste [11] Increase in sodium intake Negative but acceptable impact on colour, texture, softness, delicacy [15]
	4 times reduction (from 250 to 60 μg/kg) in cookies with $Na_4P_2O_7$ **6 times** reduction (from 250 to 40 μg/kg) in cookies with Na_4HCO_3	Cookies baked at 205° for 15 min	16	
	4 times reduction (from 180 to 45μg/kg)	Complete replacement of NH_4HCO_3 by $NaHCO_3$ in biscuits (cooking for 5 min a 230°C)	12	
Replace fructose with glucose	Minimal effect	Model dough system	17	
	8 times reduction (from 103.98 to 12.69 μg/kg)	Model dough systems (20 min at 180°C)	3	
	Ambiguous effect	Model sugars/Asn system	18	
Use asparaginase	Range reduction **from 23 to 75 %** depending mainly on pH value of	Cookies baked at 205° for 15 min	16	

	dough and time of enzyme incubation			
	84% reduction up to 58 µg/kg in treated biscuits	Asparaginase from *Aspergillus oryzae* in semisweet biscuits (cooking for 5.5 min at 260°C)	19	
	85% reduction	Asparaginase from *E.coli* in crakers	20	
	Up to **70%** (depending on enzyme concentration and incubation time and temperature)	Biscuits	21	
	Up to **97%** reduction (depending on enzyme concentration and incubation time)	Ginger bread (cooking 5 min at 250°C)	15	
	40% decrease (from 357 to 210 µg/kg)	Wheat-wholemeal oat fermented bread (500 U asparaginase per loaf)	22	
	Up to **88%** reduction	Whole-wheat bread crisp (2000U asparaginase/ kg of flour)	10	
	2 times reduction with 210 ASNU asparaginase/kg flour **2 times** reduction with 525 ASNU asparaginase/kg flour **11 times** reduction with 1050 ASNU asparaginase/kg flour	Semisweet biscuit	23	

Table 4S Literature review about relevant papers supporting each mitigation strategy in potato products

Mitigation strategy	Mitigation effect	Experimental parameters	Reference	Side effect
Add disodium diphosphate	**7 times** reduction (from 452 to 58 ng/g)	Fried sweet potatoes (5 min a 165°C) after soaking in 0.5% acid pyrophosphate	19	Possible sensory defects occurring as a result of acrylamide-lowering additives such as citric acid, could in some cases be covered up using flavourings [26]
Blanching	**5 times** reduction (from 750 to 150 µg/kg) in potatoes fried at 150°C **2 times** reduction (from 1700 to 800 µg/kg) in potatoes fried at 200°C	Blanching in hot water at 85°C for 3.5 min	25	Blanching reduces the integrity of the potato [34] The use of $CaCl_2$ may improve product texture, but oppositely can cause a bitter aftertaste [45] Continuous replacement of the blanching water with fresh water is however not feasible, both from environmental and economical point of view [46]
	15 times reduction (from 589 to 40 µg/kg)	Potatoes fried at 150°C after blanching in 0.1M $CaCl_2$ solution	4	
	65% reduction	French fries after blanching (70°C, 10–15 min)	26	
	Up to **73%** reduction (depending on patato cultivar and storing time)	French fries after blanching at 80°C for 3 min	27	Loss of starch and consequent increased oil absorption, shrinkage of raw product leading to decreased recovery in finished product and higher input costs, and changes in finished product texture and taste [26]
	1,4 times reduction (from 3220 to 2220 µg/kg)	Domestic frying after 4.5 min soaking	28	
	54% reduction	Potato chips after 17 min blanching at 64°C	29	
	1.3 times reduction (from 2.1 to 1.6 µg/kg)	French fries after 30 min blanching	30	
	Up to **4 times** (from 600 to 150 µg/kg) depending on treatment time	Microwave-blanching	31	
Cut thicker	**1.5 time** reduction (from 1500 to 1000 ppb) increasing cut size from 8.5x8.5 mm to 10x10 mm	French fries	32	Leading to slower heating [32]
	1.5 time reduction (from 1500 to 1000 ppb) increasing cut size from 8.5x8.5 mm to 10x10 mm	French fries	33	
	5 time reduction (from 12000 to 2500 ppb) increasing slide size	Fried potato slices	33	

	from 3 mm to 15 mm			
Frying at max 175°C	**2 times** reduction (from 750 to 1700 µg/Kg) lowering temperature from 200°C to 150°C **5 times** reduction (from 12000 to 2500 µg/Kg) lowering temperature from 167°C (500 sec) to 119°C (2500 sec) **42 times** reduction (from 147 to 3.46 µg/Kg) lowering temperature from 185°C (10 sec) to 125°C (60 sec) **2 times** reduction (from 2500 to 1250 µg/Kg) lowering temperature from 220°C (8 min) to 160°C (20 min) **2 times** reduction (from 4439 to 1544 µg/Kg) lowering temperature from 185°C to 175°C **1.8 times** reduction (from 761 to 401 µg/Kg) lowering temperature from 190°C to 170°C **3.1 times** reduction (from 761 to 243 µg/Kg) lowering temperature from 190°C to 150°C	French fries Fried potato power until colour development is still good Model system: potato power in hot oil Fried potato slices Potato crisps French fries	25 35 36 37 38 39	Increasing frying time causes enhancing fat uptake [47] Potato will become soft [48]
Select low sugar varieties	Variability from 104 to 296 µg/kg (**2.8 times**) Variability from 1660 to 7110 µg/kg (**4.3 times**) Variability from to 40 to 880 µg/kg (**22 times**) Variability from 230 to 650 µg/kg (**2.8 times**)	Fried potatoes from 16 different varieties (5 min at 180°C) Fried potatoes from 10 different varieties (7.5 min at 140°C) Fried potatoes (at 175°C for 150 s) from 10 different varieties Fried potatoes from 4 different varieties (5 min at 180°C)	40 41 42 43	Only a few of selected cultivar have acceptable sensory and nutritional quality [39] Difficult to control the whole production chain and agronomic factors

Store potatoes in controlled conditions	**10 times** reduction (from 2000 to 200 µg/kg) storing potatoes at 8°C and not at 4°C	Fried potatoes from 22 weeks old tubers	40	At lower preservation temperatures, sprouting can be inhibited without the use of chemicals and the potatoes are less susceptible to diseases
	6 times reduction (from 5000 to 800 µg/kg) storing potatoes at 8°C and not at 4°C	Fried potatoes from 24 weeks old tubers	38	
	2 times reduction (from 4000 to 1900 µg/kg) storing potatoes at 8°C and not at 4°C	Crisp from 18 weeks old tubers	38	
	2.5 times reduction (from 12500 to 5000 µg/kg) controlling atmosphere composition (9% O_2 - 12% CO_2 vs 18%O_2 3% CO_2)	Fried potatoes from 24 weeks old tubers	44	
Suppress sprouting	**1.7 time** reduction (from 415 to 242 µg/kg) using CIPC	Fried potatoes (2 min at 180°C)	40	Chemical sprout suppressing is not always an option due to customer demand [46]

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