Deliverable 5.3 – Agenda for the Next Five Years for Health Impacts of Maillard Reaction Products Research (2027-2031)

ACRYRED COST Action CA21149

Working Group 5: Risk-Benefit of Maillard Reaction Products and Impact of Mitigation Measures

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Executive Summary

The work performed within ACRYRED highlighted the growing need for a more comprehensive understanding of the health implications of Maillard Reaction Products (MRPs) generated during food processing. While considerable progress has been achieved in the identification, quantification and mitigation of acrylamide in foods, important scientific uncertainties remain regarding the actual health significance of long-term dietary exposure and the broader consequences of food processing for human health.

Working Group 5 was established to address these challenges through a multidisciplinary approach integrating food chemistry, toxicology, epidemiology, nutrition, exposure assessment and food technology. Throughout the Action, discussions repeatedly demonstrated that future research should move beyond the study of individual contaminants and focus on the overall health impact of food processing interventions.

The priorities presented in this roadmap are informed by a comprehensive evidence-mapping exercise conducted within WG5, including two large systematic reviews addressing complementary questions. The first review evaluates the health implications of dietary acrylamide exposure, while the second assesses mitigation measures and their effects on food quality and nutritional characteristics. Together, these activities have enabled the identification of major knowledge gaps and emerging research needs across the entire pathway from contaminant formation to health outcomes.

A key conclusion emerging from WG5 is that future research should no longer be driven solely by the question of how to reduce acrylamide concentrations in foods. Instead, scientific efforts should focus on understanding how food processing can be optimized to minimise health risks while maintaining nutritional value, sensory quality and consumer acceptance. This transition from contaminant-centred research towards integrated risk-benefit assessment represents the core strategic direction proposed for the next five years.

The present roadmap outlines the major scientific challenges, strategic priorities and implementation steps considered necessary to support evidence-based policy development, future European research initiatives and innovation in the food sector between 2027 and 2031.

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Objectives of the document

The objective of this document is to fulfil ACRYRED Deliverable 5.3: to propose a strategy for Acrylamide Research in the Fields of Health Impact of Maillard Reaction Products (2027-2031).

Current Situation and Scientific Context

More than two decades after the discovery of acrylamide in food, research has entered a new stage of maturity. Considerable progress has been made in understanding formation mechanisms, identifying critical raw materials, improving analytical methodologies and developing mitigation strategies successfully implemented across many food sectors.

At the same time, several important questions remain unresolved. Epidemiological evidence remains inconsistent, exposure assessment methodologies continue to involve substantial uncertainty, and the long-term health significance of dietary exposure remains difficult to quantify.

Furthermore, increasing scientific attention is being devoted to the complex mixture of compounds generated during thermal food processing. Acrylamide represents only one component of a broad family of Maillard Reaction Products that may exert both beneficial and adverse biological effects. The challenge for future research is therefore no longer limited to contaminant reduction but extends to understanding the overall impact of processing on human health.

Evidence Base Supporting this Roadmap

The strategic priorities proposed in this document are based on discussions held throughout ACRYRED activities and are further supported by evidence-synthesis initiatives carried out within WG5.

Two complementary systematic reviews were established to address the two fundamental scientific questions that have guided WG5 activities throughout the Action:

Why should acrylamide exposure be reduced?

and

How can acrylamide levels be reduced without compromising food quality, nutritional value and consumer acceptance?

The first review focuses on health risks associated with dietary acrylamide exposure and evaluates evidence from in vitro studies, experimental animal studies, biomonitoring investigations and human epidemiological research.

The second review examines mitigation strategies in cereal-based foods, evaluating their effectiveness, practical applicability and potential impacts on nutritional and sensory quality.

Together, these reviews provide an evidence-based assessment of current knowledge, identify persistent uncertainties and support the prioritisation of future research areas. Importantly, they establish a framework linking contaminant formation, technological interventions, dietary exposure and health outcomes, thereby supporting the integrated risk-benefit approach proposed by WG5.

Major Scientific Challenges

Challenge 1. Limited Evidence on Human Health Effects

Despite extensive toxicological research, substantial uncertainty remains regarding the actual health implications of dietary acrylamide exposure. Although experimental studies consistently demonstrate carcinogenic, neurotoxic and reproductive effects in laboratory animals, epidemiological investigations in human populations have produced inconsistent results.

One of the major reasons for this uncertainty lies in limitations of current exposure-assessment methods, insufficiently validated biomarkers and variability in dietary habits across populations.

Future progress requires large multicentre cohort studies, improved biomonitoring approaches and more robust exposure assessment methodologies capable of reducing uncertainty in human risk evaluation.

Challenge 2. Insufficient Understanding of Biological Mechanisms

The biological pathways linking dietary exposure to disease development remain incompletely understood. Current knowledge relies heavily on animal models and in vitro studies, while translation of these findings to realistic dietary exposure levels remains challenging.

Future research should place greater emphasis on mechanistic toxicology, adverse outcome pathways, systems biology and omics technologies. Improved understanding of molecular mechanisms is essential for strengthening causal interpretation of epidemiological observations and improving risk assessment.

Challenge 3. Limited Understanding of the Health Significance of Other Maillard Reaction Products

Research conducted over the past two decades has focused predominantly on acrylamide, resulting in a fragmented understanding of the broader spectrum of Maillard Reaction Products generated during thermal processing.

Many MRPs may exert beneficial biological effects, including antioxidant, antimicrobial and prebiotic activities. Conversely, certain compounds such as furans, hydroxymethylfurfural and advanced glycation end-products may contribute to adverse health outcomes.

A comprehensive evaluation of the health impacts of thermal food processing must therefore consider the entire spectrum of beneficial and harmful compounds rather than individual contaminants in isolation.

Challenge 4. Uncertainty Regarding the Consequences of Mitigation Measures

Numerous mitigation strategies have successfully reduced acrylamide concentrations in foods. However, relatively limited attention has been devoted to understanding their broader effects on nutritional quality, organoleptic characteristics, commercial feasibility and consumer behaviour.

Changes in raw materials, reformulation approaches and process modifications can affect flavour, colour, texture, nutrient retention and overall product acceptability.

Future studies should therefore assess mitigation measures within a broader framework encompassing both contaminant reduction and overall product quality.

Challenge 5. Lack of Integrated Risk-Benefit Assessment Frameworks

Current regulatory and technological decision-making often focuses either on reducing risks or on preserving product quality and nutritional value. Few methodologies are currently available to evaluate both aspects simultaneously.

WG5 identified the development of integrated risk-benefit assessment frameworks as one of the most important priorities for future research. Such frameworks should combine toxicological, nutritional, technological, consumer and economic considerations within a common decision-support system.

Overview of Challenges and Strategic Priorities

Major Challenge	Strategic Priority	Expected Outcome
Limited evidence on human health effects	Human epidemiology and biomonitoring	Reduced uncertainty regarding health risks
Limited mechanistic understanding	Mechanistic toxicology	Improved biological understanding and validated biomarkers
Narrow focus on acrylamide	Health effects of Maillard Reaction Products	Comprehensive assessment of beneficial and adverse MRPs
Uncertain internal exposure	Bioavailability and metabolism studies	Improved exposure assessment
Limited understanding of mitigation consequences	Integrated risk-benefit assessment	Balanced mitigation strategies
Limited consumer evidence	Consumer behaviour and risk communication	Improved adoption of mitigation recommendations
Lack of predictive tools	Digital tools and predictive modelling	Decision-support systems for stakeholders

Strategic Priorities for 2027-2031

Priority 1. Human Epidemiology and Biomonitoring

Generation of robust human evidence should remain the highest priority for future research. Efforts should focus on harmonised biomonitoring programmes, improved biomarkers of exposure and effect, and large prospective cohort studies capable of reducing uncertainty regarding long-term health outcomes.

Priority 2. Mechanistic Toxicology

Future research should improve understanding of the molecular mechanisms underlying acrylamide toxicity, including DNA damage, oxidative stress, inflammation, epigenetic effects and adverse outcome pathways. Integration of mechanistic toxicology and epidemiology will be essential for improving risk characterisation.

Priority 3. Health Effects of Maillard Reaction Products

Research should expand beyond acrylamide and address the broader spectrum of compounds formed during thermal processing. Particular attention should be devoted to understanding interactions among MRPs and evaluating both beneficial and adverse biological effects.

Priority 4. Internal Exposure, Bioavailability and Metabolism

A better understanding of absorption, metabolism, distribution, elimination and microbiome interactions is necessary to improve interpretation of dietary exposure. Internal exposure metrics should increasingly complement traditional intake-based approaches.

Priority 5. Integrated Risk-Benefit Assessment

Future studies should develop methodologies that simultaneously evaluate health risks, nutritional value, sensory quality, consumer acceptance and economic feasibility. Such approaches are essential for supporting evidence-based decision-making in food innovation and regulation.

Priority 6. Consumer Behaviour and Risk Communication

The success of mitigation strategies ultimately depends on consumer adoption and trust. Research should therefore investigate consumer perception, communication of scientific uncertainty and behavioural responses to dietary recommendations.

Priority 7. Digital Tools and Predictive Modelling

Advances in artificial intelligence, machine learning and computational modelling offer opportunities for improving exposure assessment, identifying emerging risks and supporting scenario-based decision-making. These approaches should become increasingly integrated into food safety research and risk assessment.

Five-Year Roadmap

Phase I: Evidence Consolidation and Harmonisation (2027-2028)

The first phase should focus on consolidating current knowledge and strengthening research infrastructure. Particular emphasis should be placed on publication of evidence syntheses, harmonisation of methodologies, biomarker validation and the creation of shared European databases.

Expected outcomes:

- consolidated evidence base;
- harmonised protocols;
- coordinated research infrastructure;
- prioritised knowledge gaps.

Phase II: Knowledge Generation and Integration (2028-2030)

The second phase should focus on generating new evidence through interdisciplinary studies addressing the main knowledge gaps identified in Phase I. Particular emphasis should be placed on epidemiological investigations, mechanistic studies and integrated assessments of MRPs.

Expected outcomes:

- improved understanding of health effects;
- validated biomarkers;
- comprehensive MRP datasets;
- prototype risk-benefit assessment models.

Phase III: Translation into Policy and Practice (2030-2031)

The final phase should focus on implementation and translation of research findings into practical applications supporting regulators, industry and public-health stakeholders.

Expected outcomes:

- evidence-based recommendations;
- decision-support tools;
- industrial guidance documents;
- improved policy support.

Recommendations for Stakeholders

Researchers

Promote multidisciplinary projects integrating food chemistry, toxicology, nutrition, epidemiology, exposure science and consumer research.

Funding Agencies

Support long-term research programmes addressing health impacts of food processing and integrated risk-benefit assessment.

Regulatory Authorities

Promote harmonised assessment methodologies and encourage incorporation of risk-benefit approaches into future food-safety frameworks.

Food Industry

Continue implementation of mitigation measures while maintaining product quality, nutritional value and consumer acceptance.

Scientific Networks

Build upon the collaborations established through ACRYRED to develop long-term European networks addressing process contaminants and Maillard Reaction Products.

Vision for 2031

By 2031, Europe should possess significantly stronger scientific evidence regarding the health implications of dietary acrylamide exposure and other Maillard Reaction Products. Scientific uncertainty should be substantially reduced through harmonised methodologies, validated biomarkers, improved biomonitoring systems and large-scale interdisciplinary studies.

The evidence-synthesis activities initiated within WG5 should evolve into a dynamic knowledge platform capable of continuously informing research priorities, regulatory developments and industrial practices.

Most importantly, future research should move beyond the narrow objective of contaminant reduction alone and support optimisation of food-processing systems that maximise health benefits while minimising risks. Such an approach will provide a stronger scientific basis for innovation, regulation and public-health protection across the European food system.

Conclusions

The work performed within WG5 demonstrates that the future of acrylamide research lies not only in reducing contaminant concentrations, but in understanding the broader health consequences of food processing. The challenge for the coming decade is therefore to develop scientific approaches capable of simultaneously considering food safety, nutritional quality, consumer acceptance and public health.

The roadmap presented here provides a framework for achieving this goal and represents a lasting legacy of the ACRYRED network. Through continued interdisciplinary collaboration and evidence-based research, Europe will be better positioned to develop food-processing strategies that support safe, nutritious and sustainable diets for future generations.

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