Acrylamide in Cereal Products: Progress and Prospects
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Acrylamide: Formation, Mechanism and Reactions

Vural Gökmen

Hacettepe University
Department of Food Engineering
Food Quality and Safety (FoQuS) Research Group

Food Quality & Safety
https://foqus.hacettepe.edu.tr
foqus@hacettepe.edu.tr

Levels in Different Foods

Potato chips
- Mean 675 µg/kg
- Max 4533 µg/kg
- BL 750 µg/kg

Biscuits, crackers
- Mean 680 µg/kg
- Max 3307 µg/kg
- BL 350-400 µg/kg

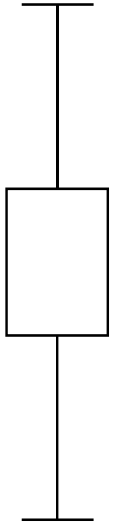
Roasted coffees
- Mean 393 µg/kg
- Max 7095 µg/kg
- BL 400 µg/kg

Breakfast cereals
- Mean 155 µg/kg
- Max 2072 µg/kg
- BL 300 µg/kg

Baby foods
- Mean 69 µg/kg
- Max 1200 µg/kg
- BL 40 µg/kg

French fries
- Mean 338 µg/kg
- Max 2174 µg/kg
- BL 500 µg/kg

Bread
- Mean 53 µg/kg
- Max 563 µg/kg
- BL 50 µg/kg

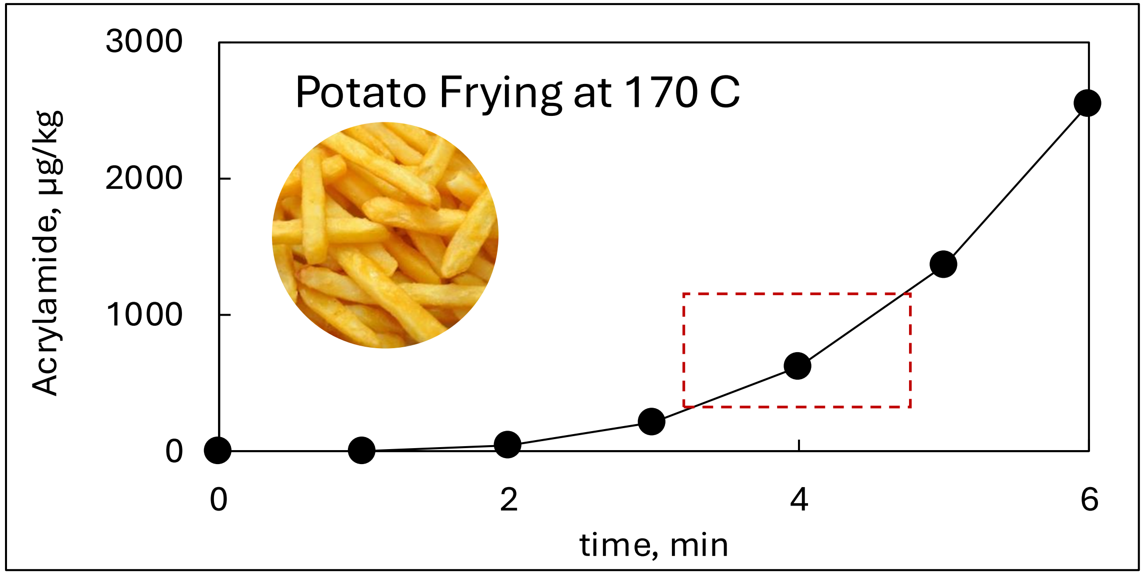


- From low ppb to ppm levels in different food categories.
- Large deviations within same food categories.

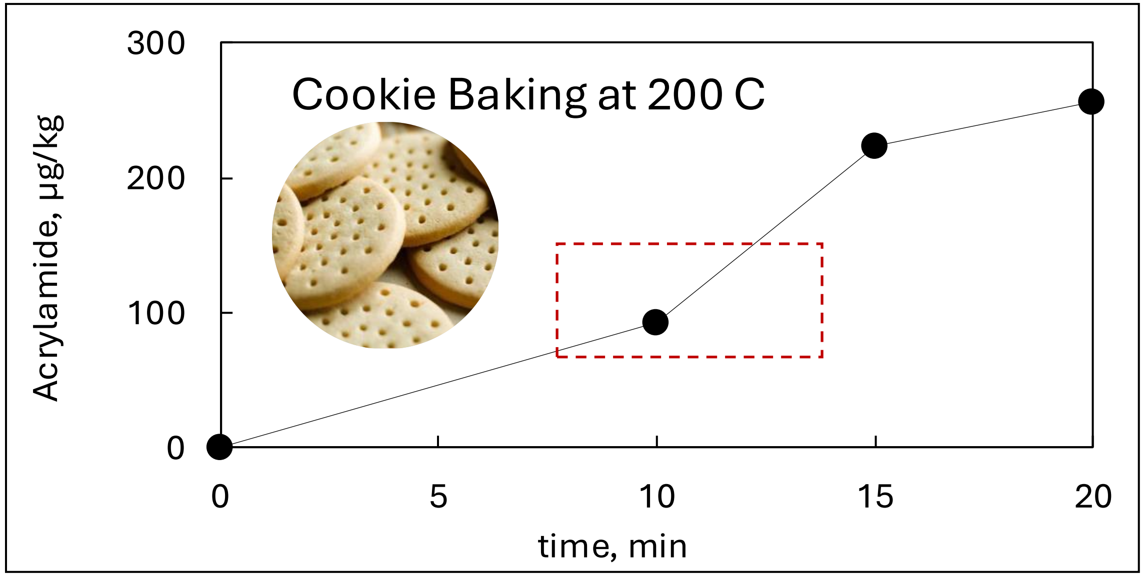
Data from EFSA's 2010 survey. BL: Benchmark Level

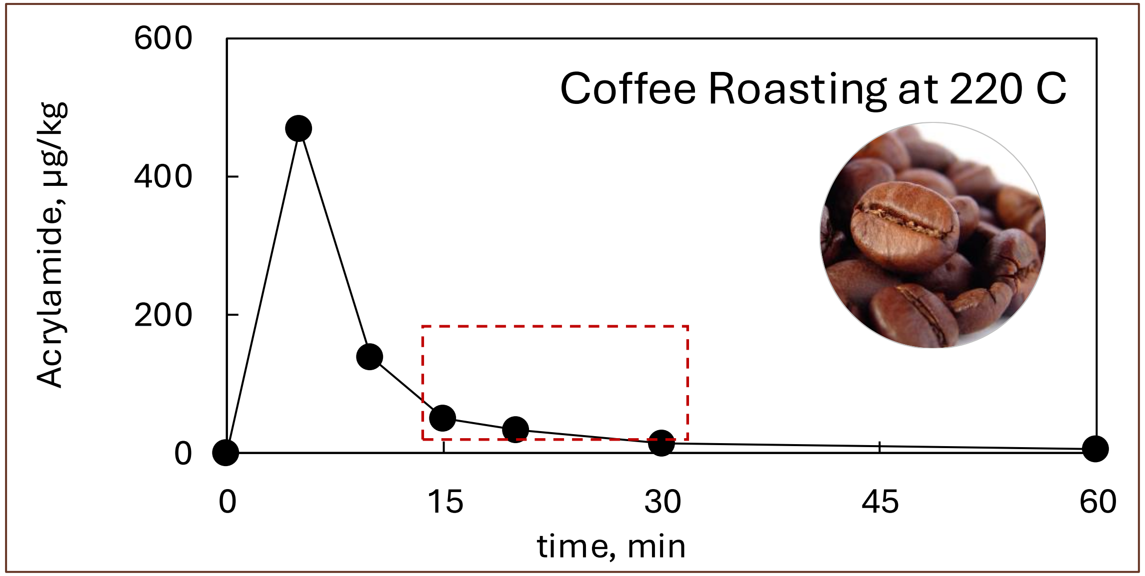
efsa
European Food Safety Authority

Kinetics when product differs



- Different food matrices
- Different (typical) T/t conditions
- Same reaction
- Different kinetics
  - Parabola (French fries)
  - Sigmoid (Cookies)
  - Peak (Roasted coffee)
- Product type and T/t matter

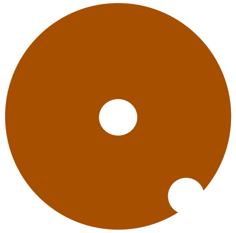




Kinetics when size differs

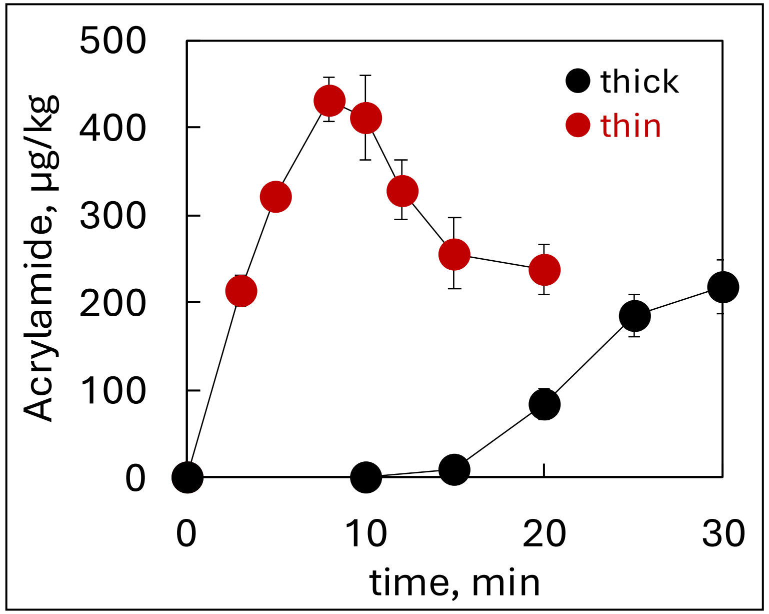
h = 0.7 cm (thick)

h = 0.1 cm (thin)

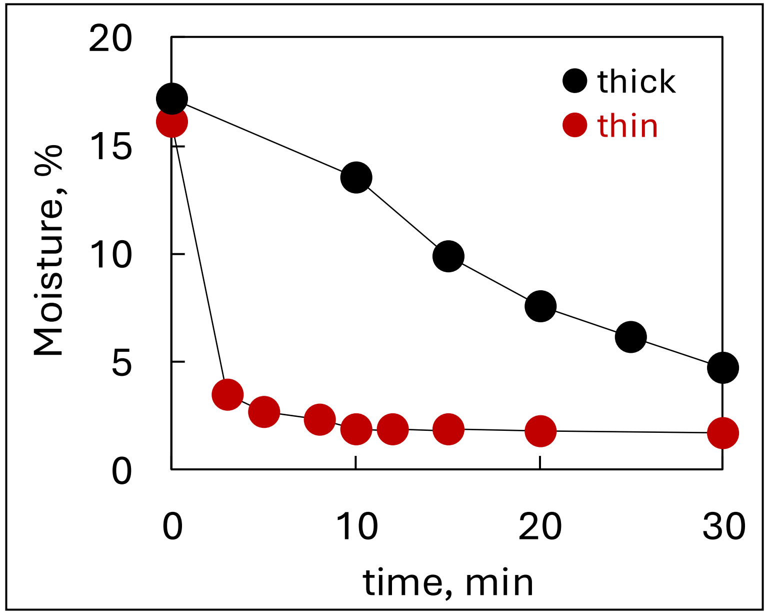


- Same food matrice
- Same baking T/t condition
- Same reaction
- Different piece sizes
- Thin piece dries faster, T rises faster, acrylamide forms faster.

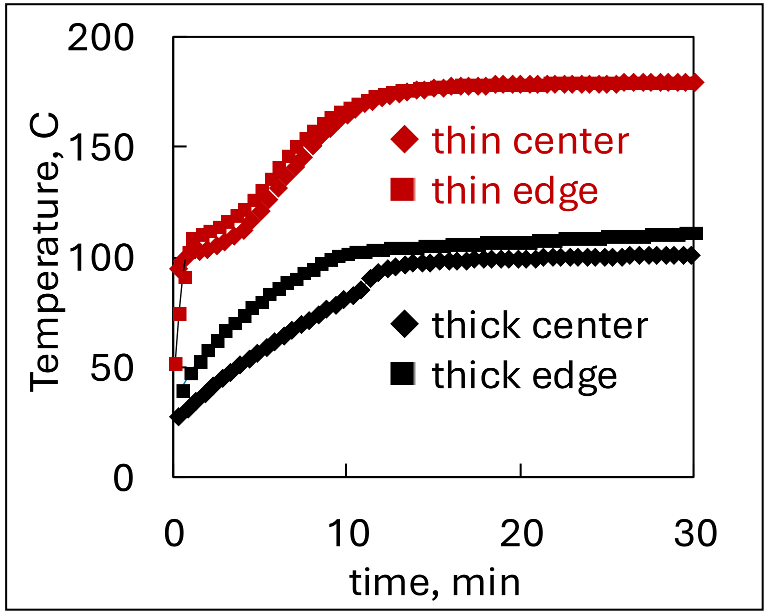
Acrylamide (µg/kg) versus time



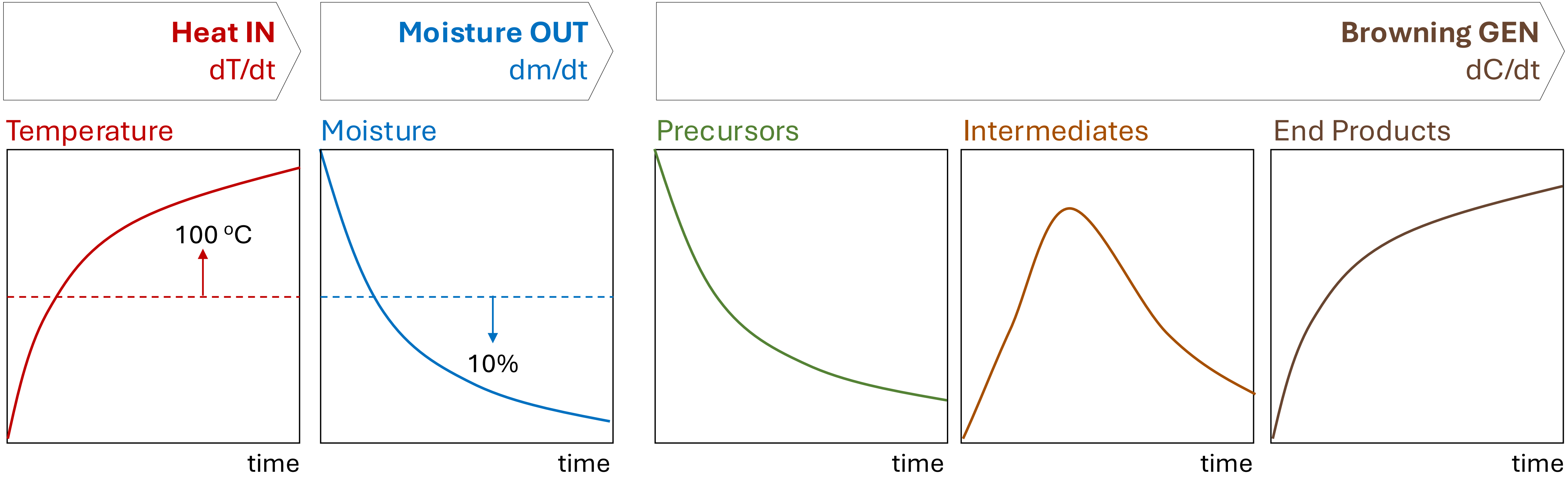
Moisture (%) versus time



Temperature (°C) versus time



Understanding the Process



The **browning reactions** accelerates when the conditions of T > 100 °C and moisture < 10% moisture are attained within the food during the cooking process.

- Cooking temperature
- Initial moisture content
- Initial concentration of precursors

Understanding the Mechanism

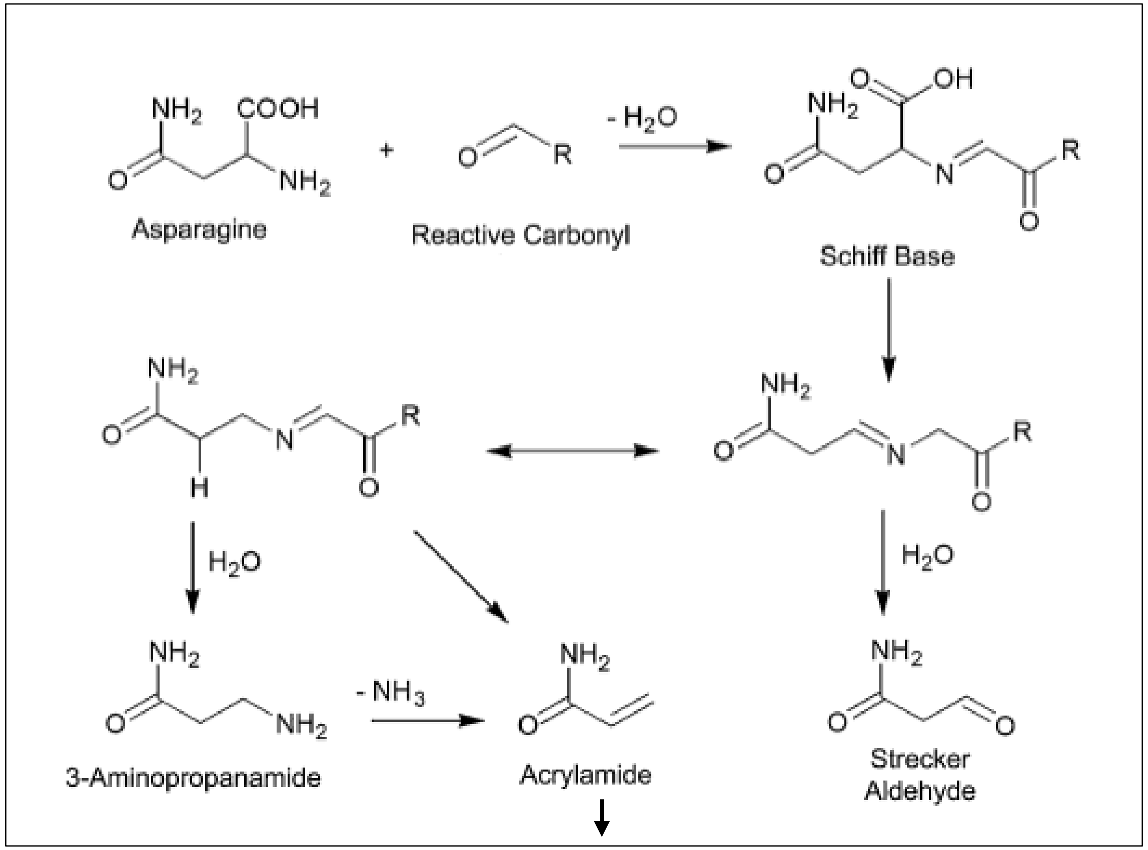
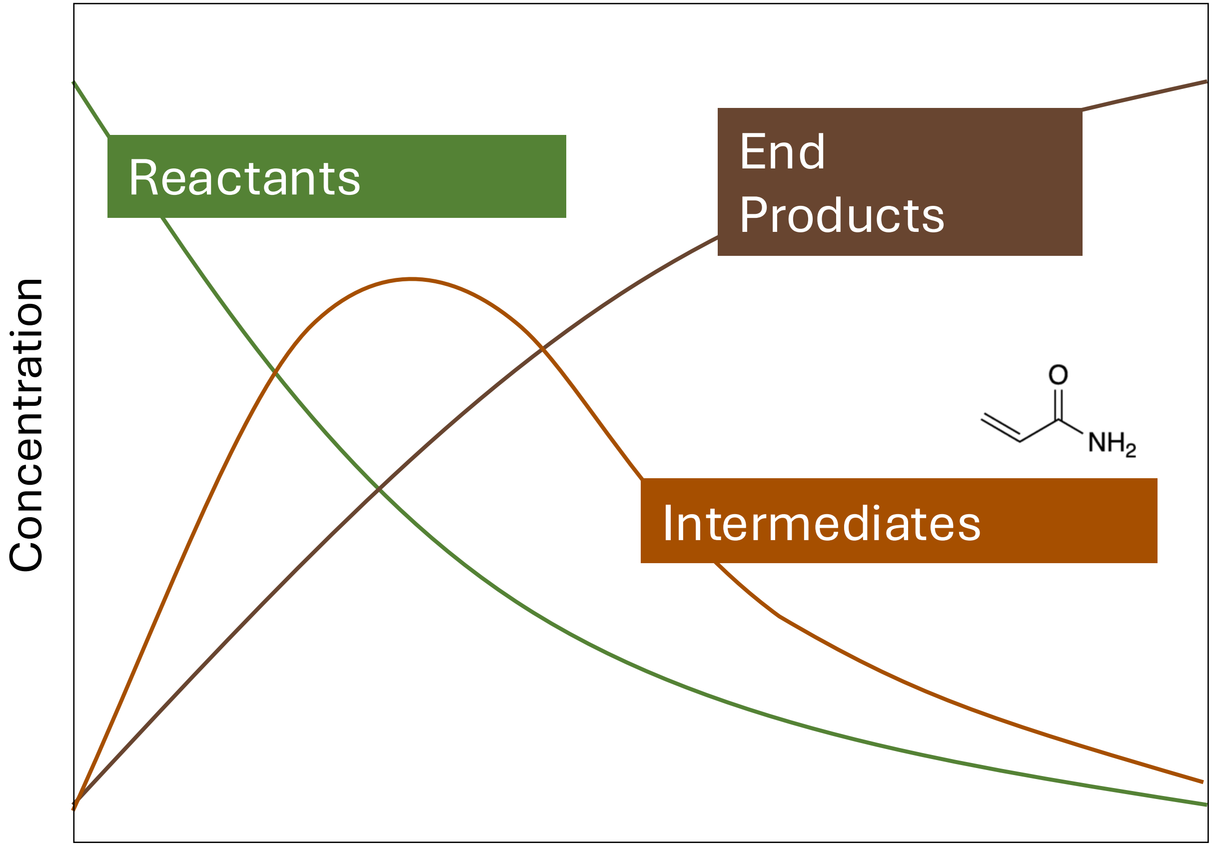


Figure Reaction mechanism for acrylamide formation in foods during cooking (Adapted from Zyzak et al. 2003, Yaylayan et al. 2003, Stadler et al. 2004)



$$\text{Rate} = dC_{Acr}/dt = f\{C_{Asn}\ C_{Car}\ T\ \text{pH}\ a_w\}$$

- Asparagine is the limiting factor.
- Carbonyl compounds are the accelerators.

Role of Carbonyl Compounds

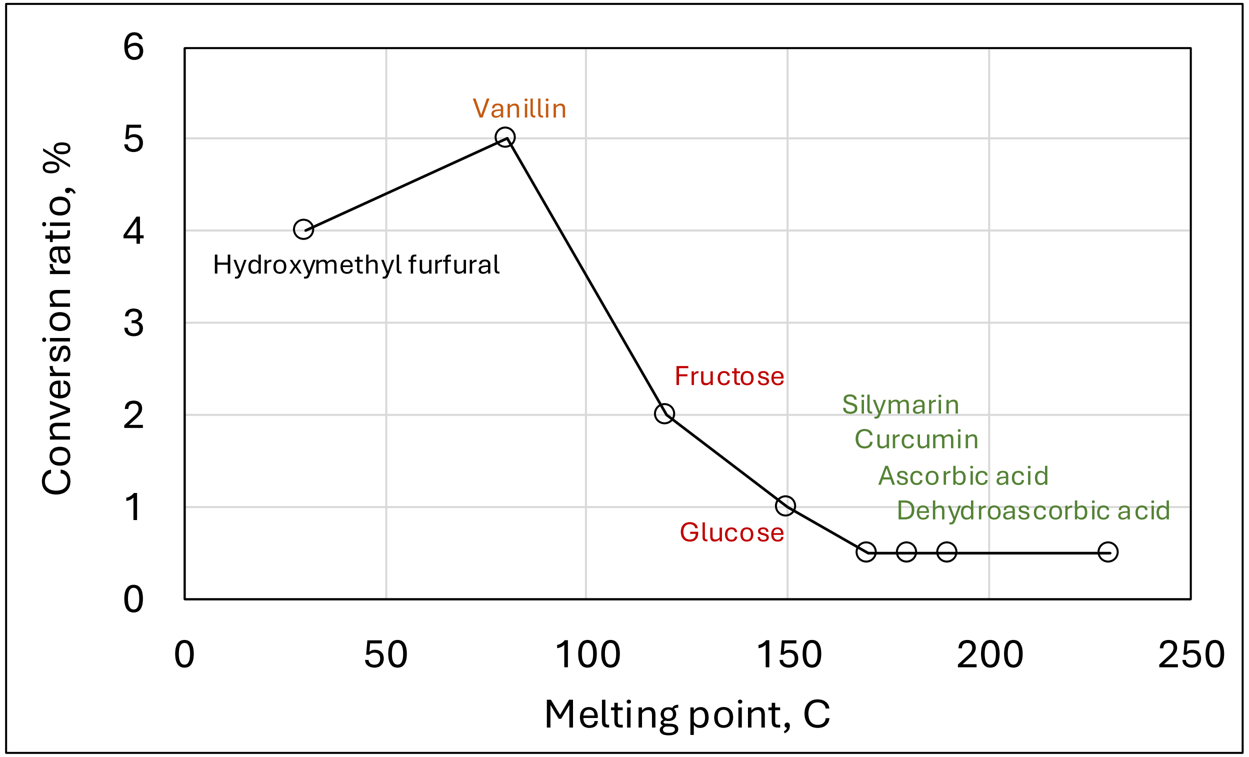
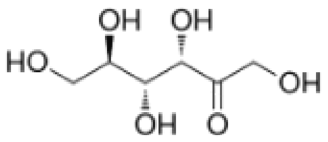


Figure The conversion ratio of asparagine into acrylamide in the presence of different carbonyl compounds during heating at 180ºC for 10 min. Hamzalıoğlu and Gökmen, 2012. Eur Food Res Technol 235, 1093–1099

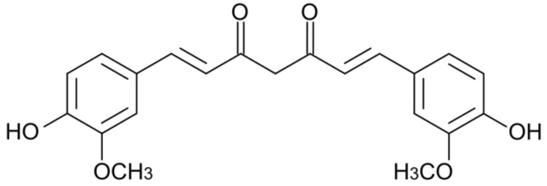
Asparagine + Carbonyl Compound

Asparagine to Acrylamide Conversion Ratio

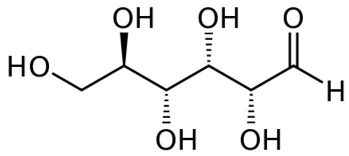
Fructose



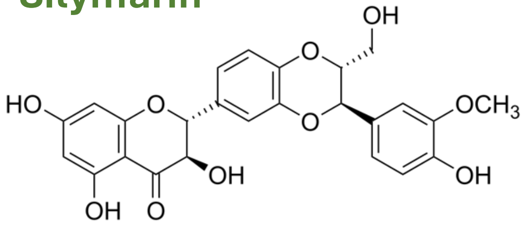
Curcumin



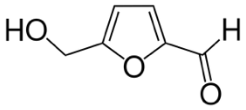
Glucose



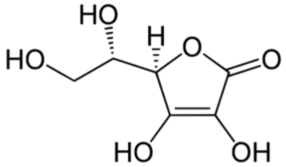
Silymarin



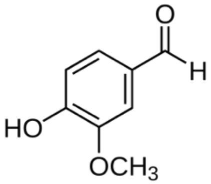
Hydroxymethyl furfural



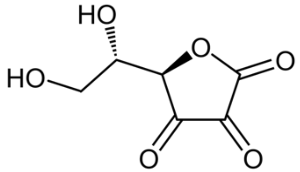
Ascorbic Acid



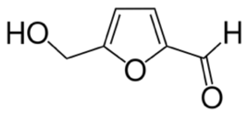
Vanillin



Dehydroascorbic Acid



Sugar Degradation: Glucose



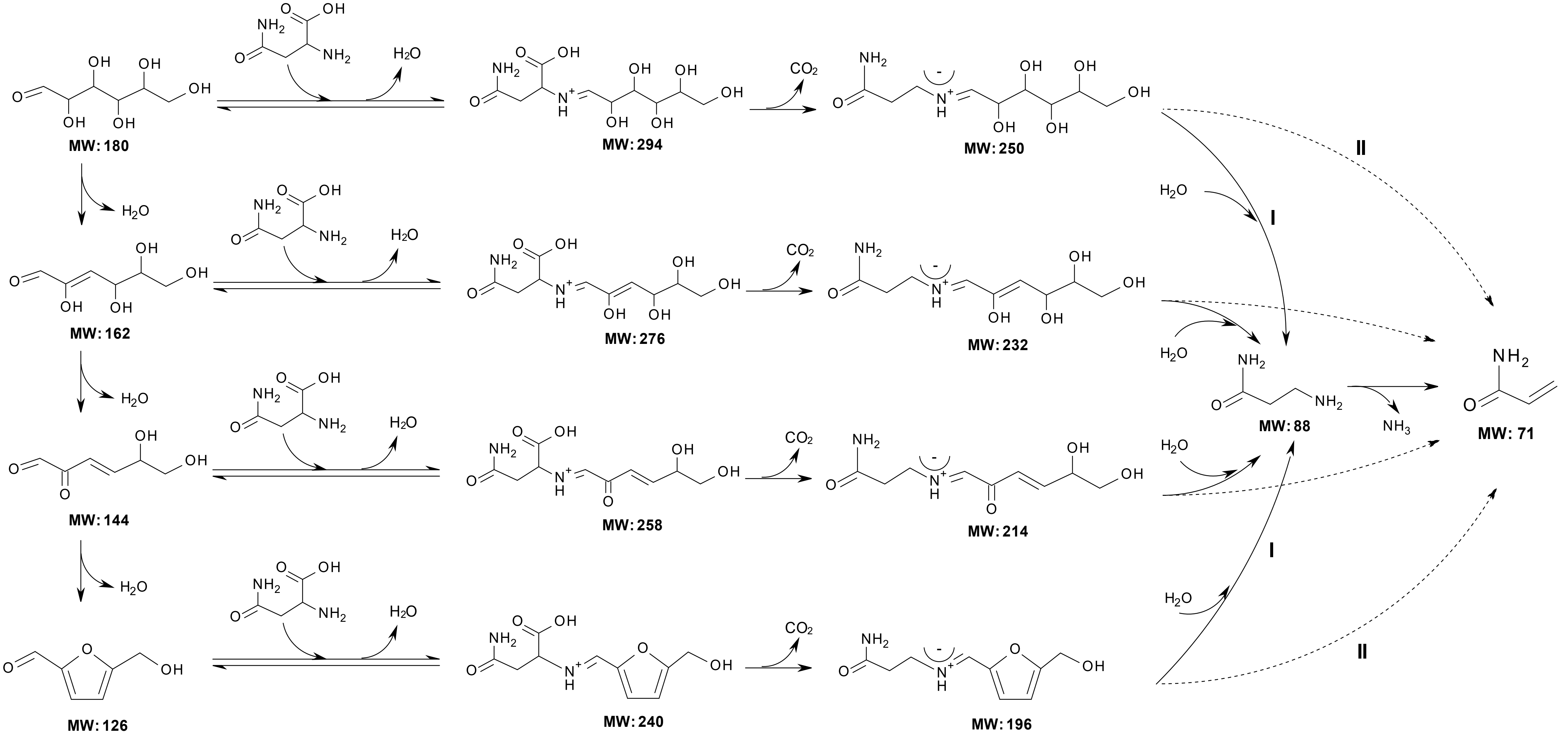
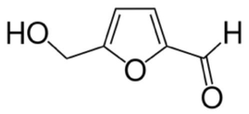
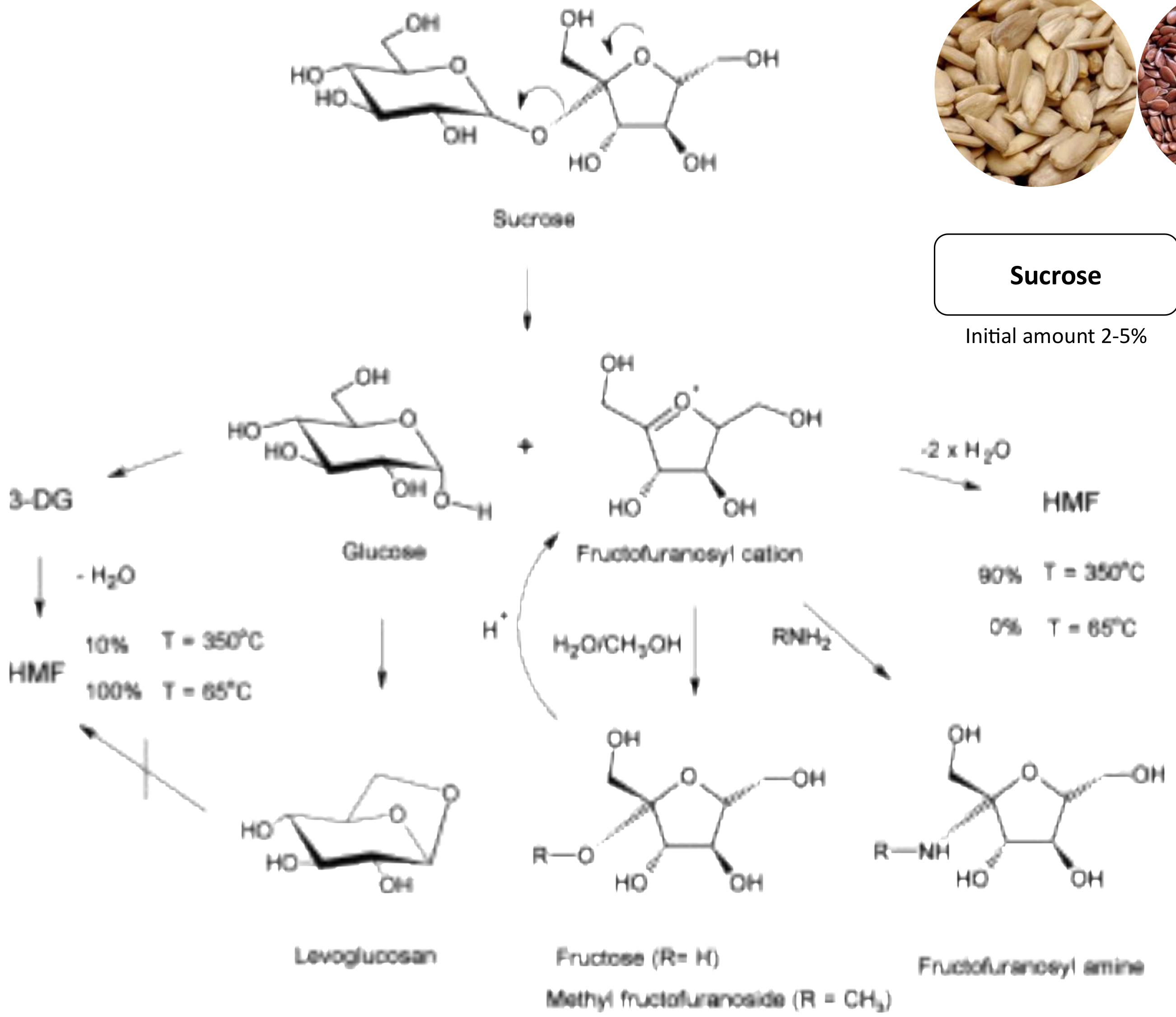


Figure Proposed mechanism of acrylamide formation from glucose and its degradation products at 180 °C. Gökmen, Kocadağlı, Göncüoğlu and Mogol, 2012. Food Chem. 132: 168-134

Sugar Degradation: Sucrose





Sucrose → **Hydroxymethylfurfural** → **Acrylamide**

Initial amount 2-5%

Upto 500 mg/kg forms (Maximum HMF yield is ~5% of reacted sucrose)

Upto 3000 µg/kg forms (Maximum acrylamide yield ~0.1% of reacted asparagine)

Asparagine

200-2000 mg/kg

Figure Proposed mechanism of thermal generation of glucose and fructofuranosyl cation from sucrose. Locas and Yaylayan 2008. J. Agric. Food Chem. 56: 6717-6723

Sucrose Degradation: Roasting

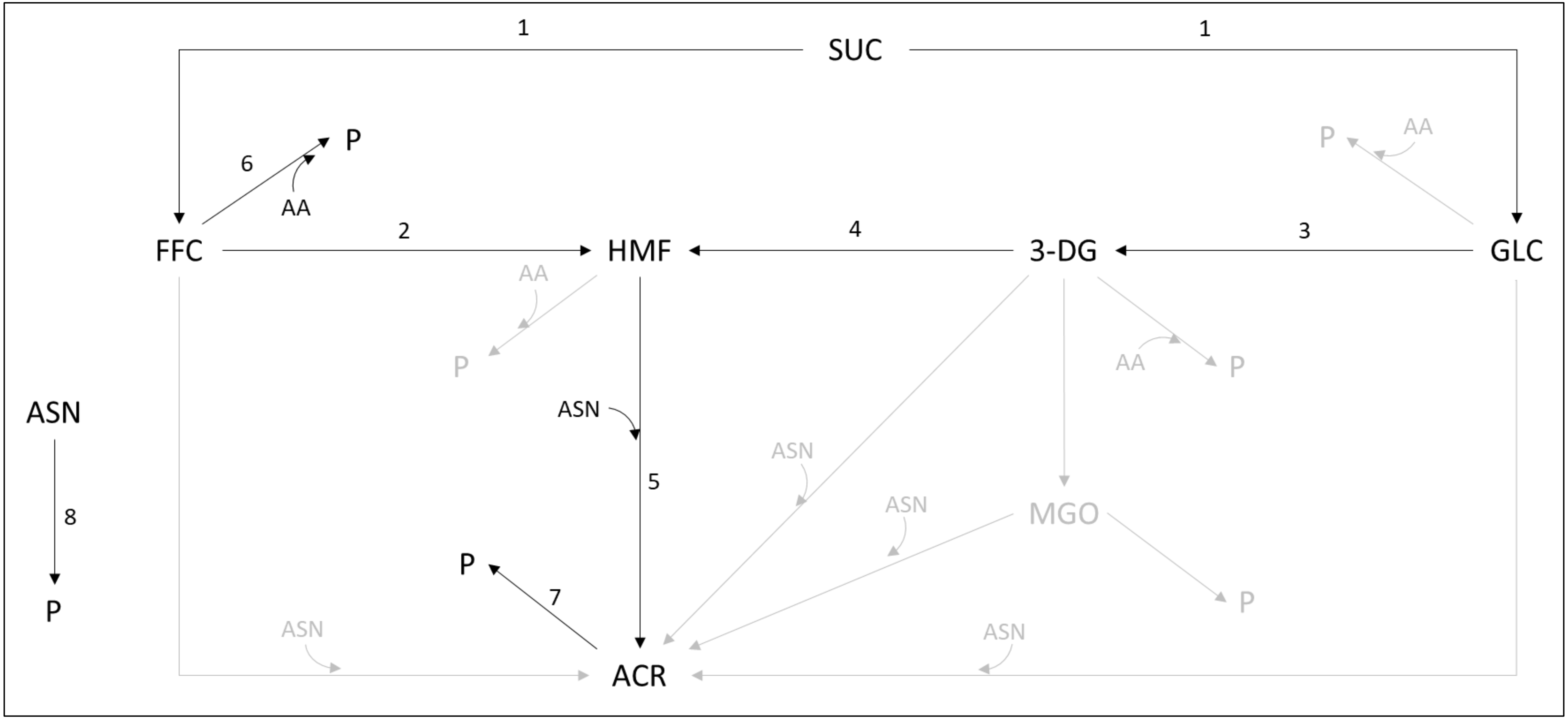
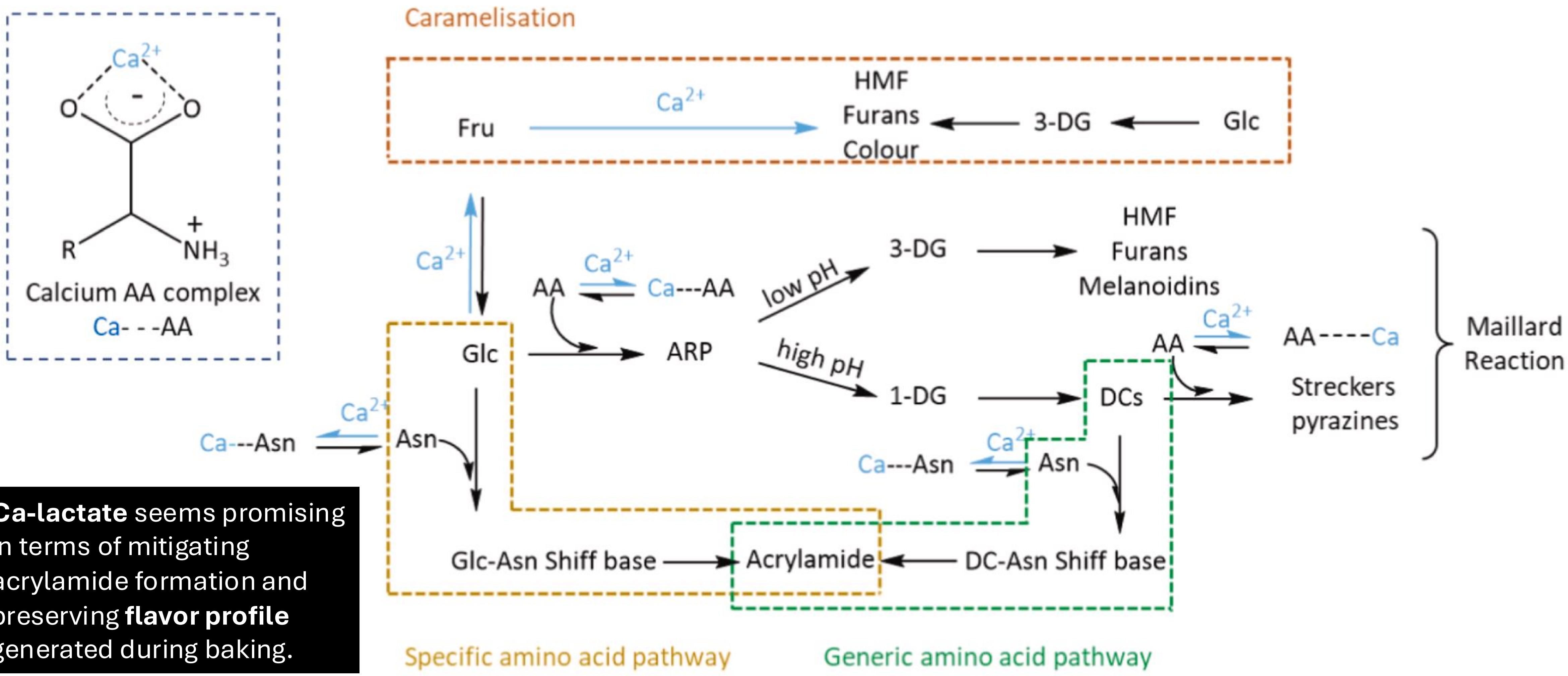


Figure Multiresponse kinetic modelling of acrylamide formation in coffee, nuts and seeds during roasting through sucrose degradation. Hamzalıoğlu and Gökmen (2020) Food Chem 318, 126467; Berk, Aktağ and Gökmen (2021) Eur Food Res Technol 247, 2285-2298; Şen and Gökmen (2023) ACS Food Sci Technol 3, 9, 1606-1616

Role of Divalent Cations: Calcium



Ca-lactate seems promising in terms of mitigating acrylamide formation and preserving **flavor profile** generated during baking.

Figure Simplified formation pathways of acrylamide, HMF and aroma compounds during heating and the effect of cations on the pathway. Taş, Kocadağlı, Balagiannis, Gökmen, Parker (2023) Food Chemistry 410 (2023) 135358

Role of Thiol Compounds: Glutathione

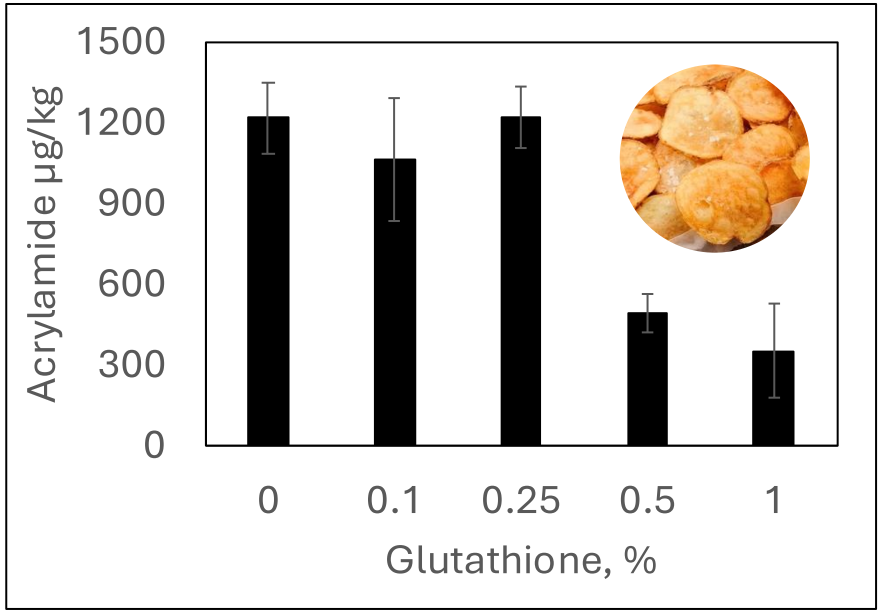
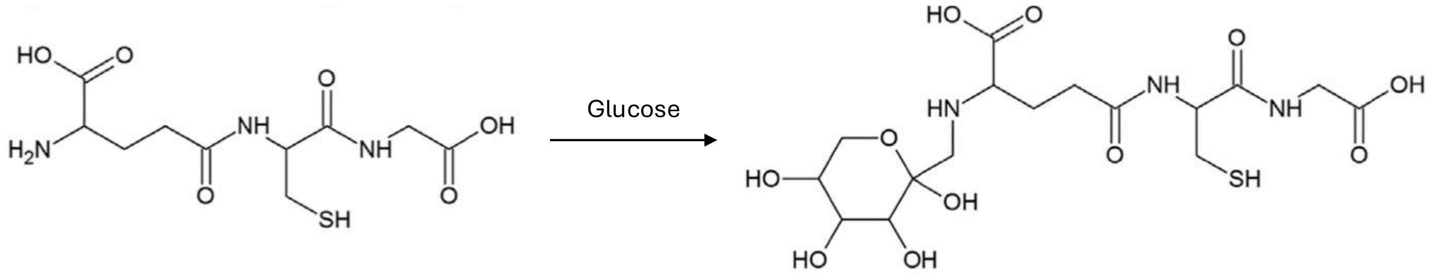


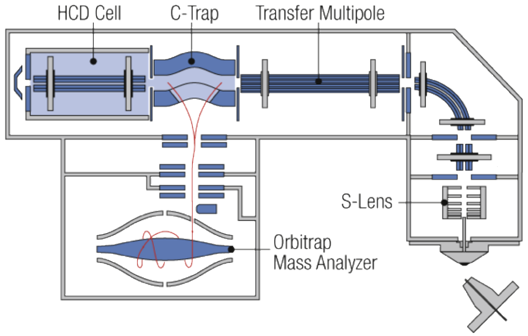
Figure Effects of different added amounts of (a) GSH and (b) cysteine on the formation of acrylamide in formulated potato chips. Mogol, Hamzalıoğlu, Şensoy and Gökmen (2025) Food Chemistry 493 (2025) 145673

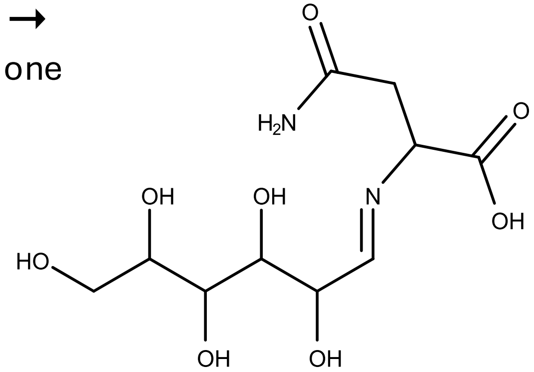


Glutathione
$C_{10}H_{17}N_3O_6S$
[M+H] 308.09108

Schiff base of Glutathione
N-(1-deoxy-D-fructos-1-yl)-glutathione
$C_{16}H_{27}N_5O_8S$
[M+H] 470.1439

Asparagine + Glutathione + Glucose → → →
Schiff base of Asparagine + Schiff base of Glutathione



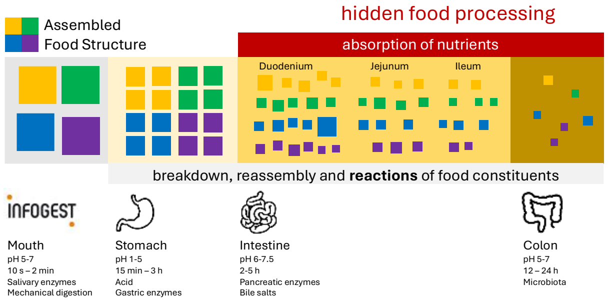


Schiff base of Asparagine
N-(1-deoxy-D-fructos-1-yl)-asparagine

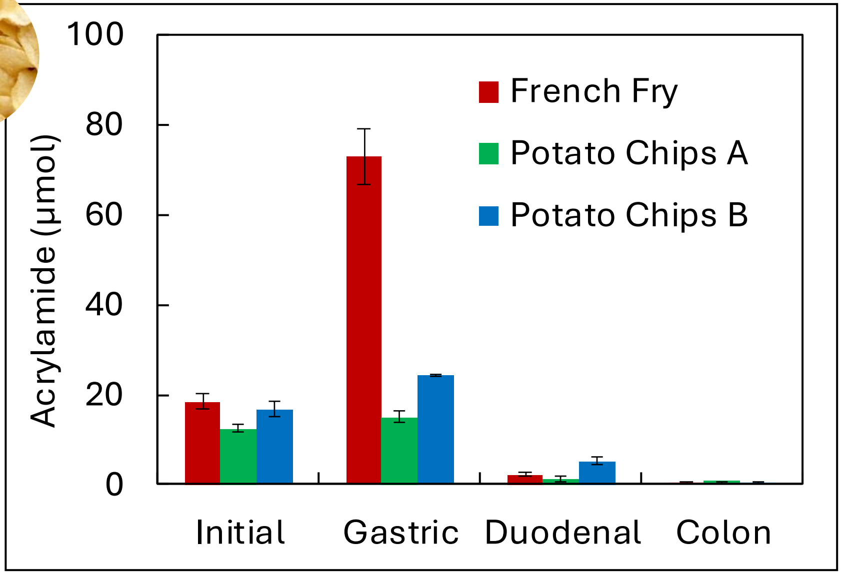
Glutathione seems promising in terms of mitigating acrylamide formation and preserving **flavor profile** in formulated potato chips..

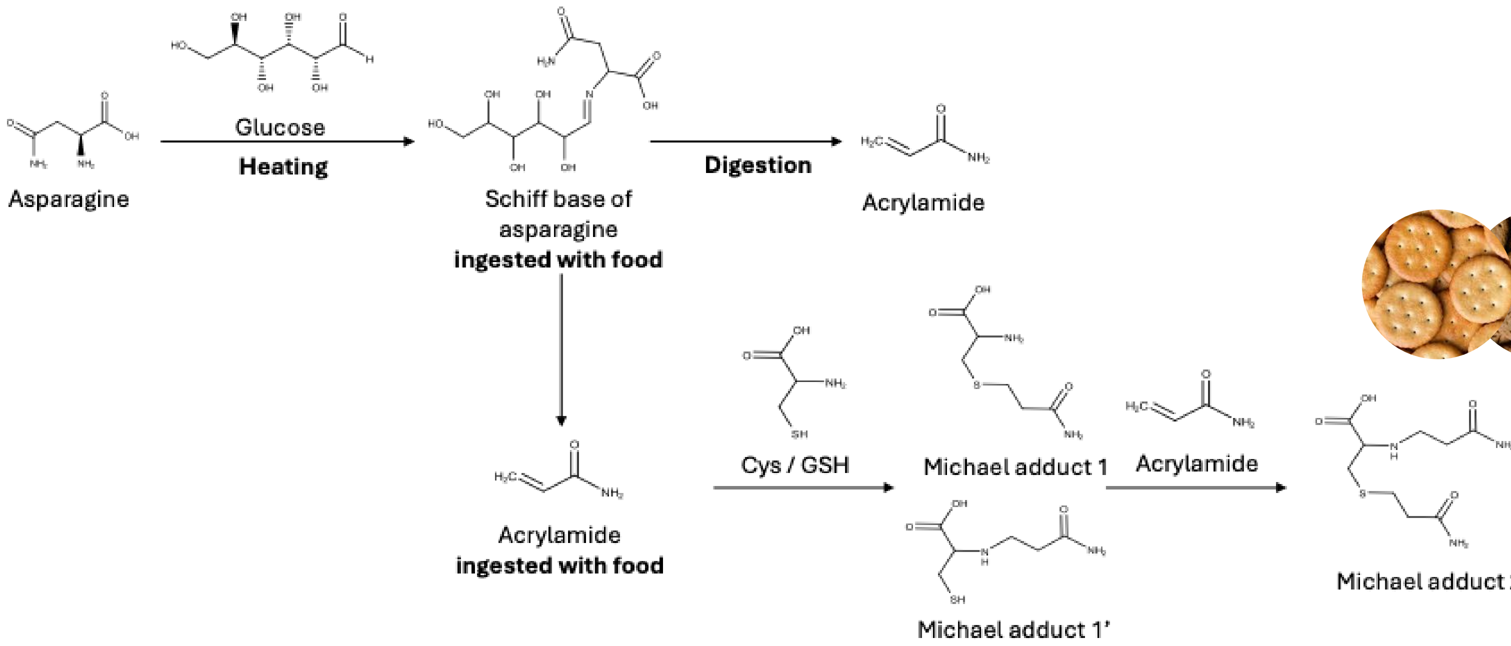
Acrylamide mitigation by glutathione is due to **competition** with asparagine toward reducing sugars as confirmed by the Schiff bases of glutathione and asparagine.

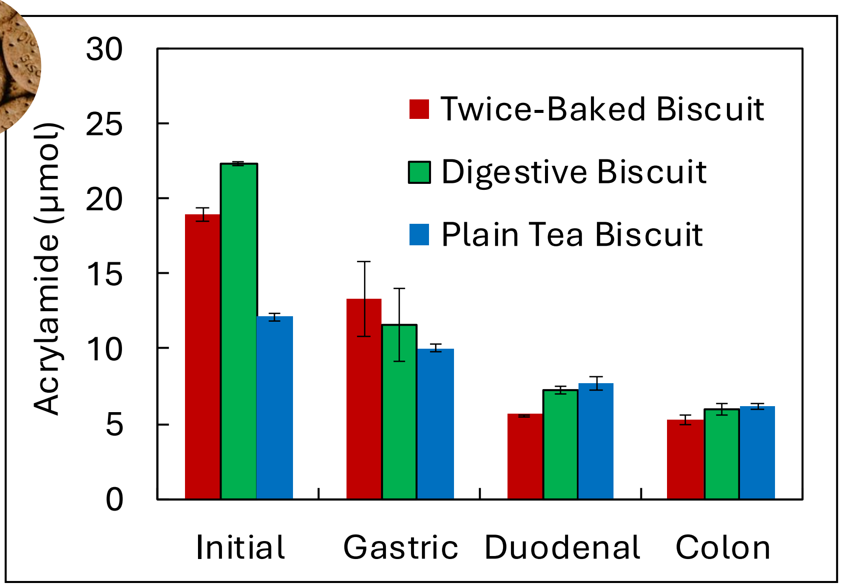
The GI Tract



Acrylamide concentrations tends to decrease during in vitro digestion. However, higher accumulation of the Schiff base of asparagine in French fries seems posing extra risk to consumers as it potentially transforms to acrylamide under gastric conditions.



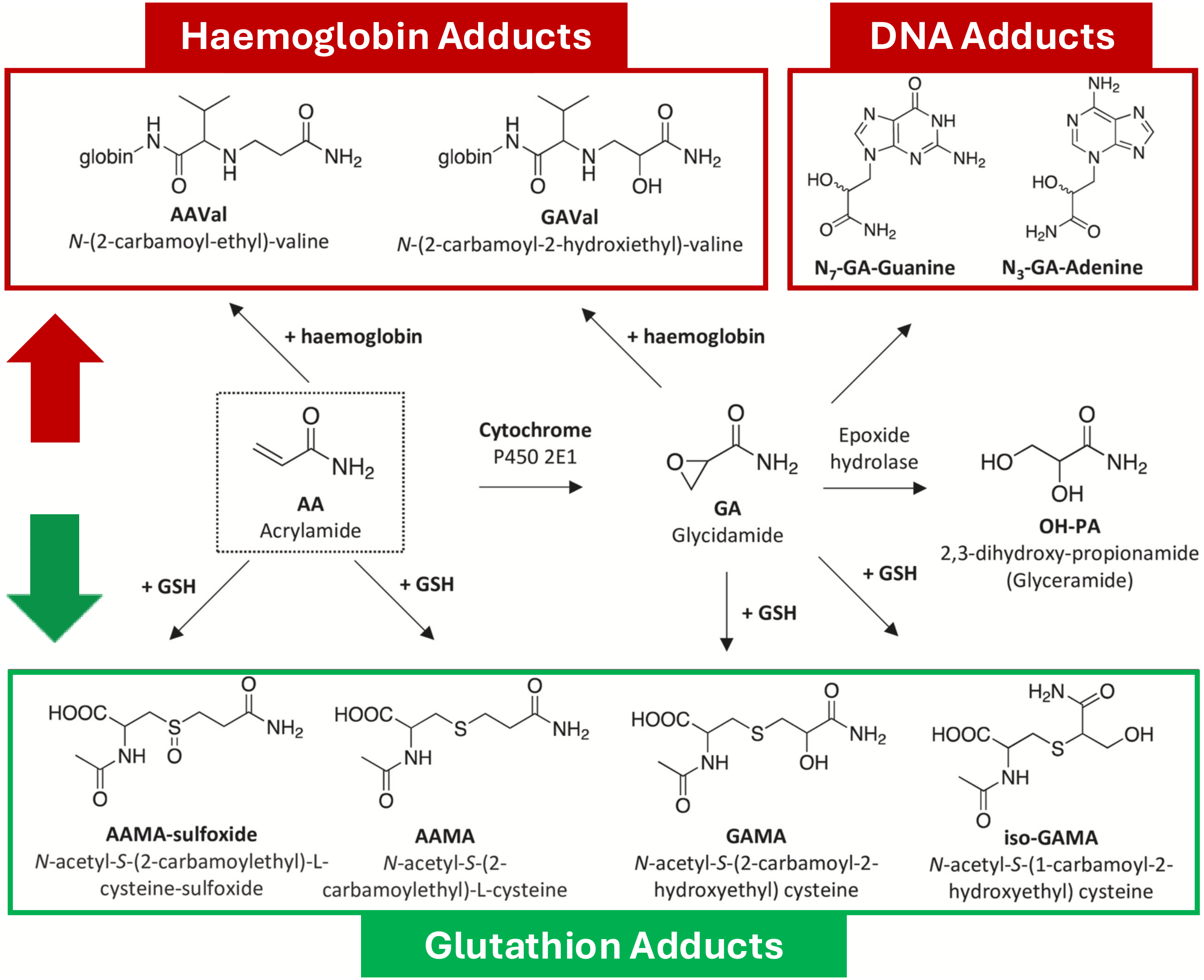




Figures

Fate of acrylamide and Schiff base of asparagine in fried potatoes and biscuits during digestion. Hamzalıoğlu and Gökmen (2015) Food & Function 6, 109-114e

Blood and Urinary Biomarkers



Toxification

Blood Biomarkers (Long-Term Exposure)

- DNA adducts
- Haemoglobin adducts

Acrylamide (AA) is readily absorbed from the GI tract and distributed to all organs. It is extensively metabolized, mostly by conjugation with **glutathione** (GSH) but also by epoxidation to glycidamide (GA). The human body produces glutathione, but there are also dietary sources.

Detoxification

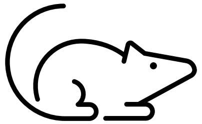
Urinary Biomarkers (Short-Term Exposure)

- Glutathione adducts (AAMA and GAMA)
- These mercapturic acid derivatives are usually excreted into the urine.

In vivo Detoxification by Thiols

Potato chips
Potato chips with 1.0% GSH
Potato chips with 0.5% Cys

Standard Chow Diet
Chow Diet with 15% Potato Chips
- Control
- 1% GSH
- 0.5% Cys



Feeding 7 days
Six-week-old male C57BL/6N mice (n=5/7)

Table Effects of potato chips reformulated with glutathione and cysteine on urinary AAMA and GAMA levels of male C57BL/6N mice. Mogol et al. J Sci Food Agric 2026; 106: 5012–5020

	Feed	Urine	
Diet	**Acrylamide µg/kg**	**AAMA µg/mL**	**GAMA µg/mL**
Standard Chow Diet	<LOD	0.0181 ± 0.002^{c}	<LOD
Chow Diet with 15% Potato Chips			
▪ Control	1155	0.0429 ± 0.006^{b}	0.0451 ± 0.006^{a}
▪ 1% GSH	315	0.0690 ± 0.016^{a}	0.0208 ± 0.003^{b}
▪ 0.5% Cys	200	0.0356 ± 0.002^{b}	0.0154 ± 0.001^{b}

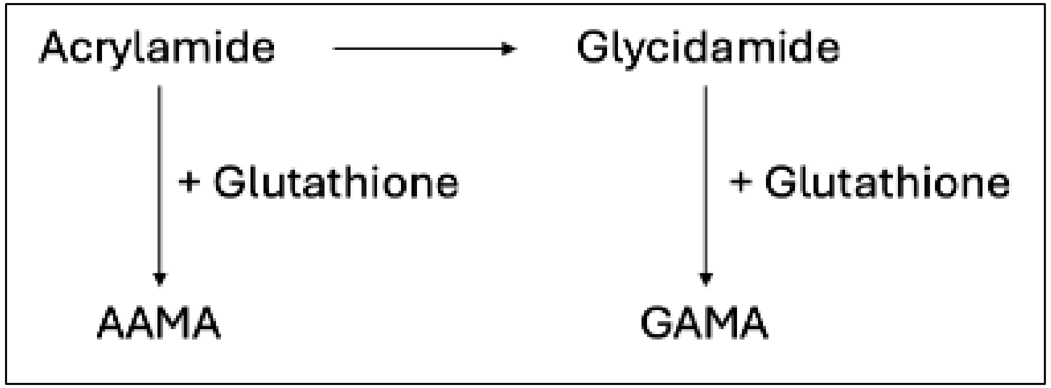
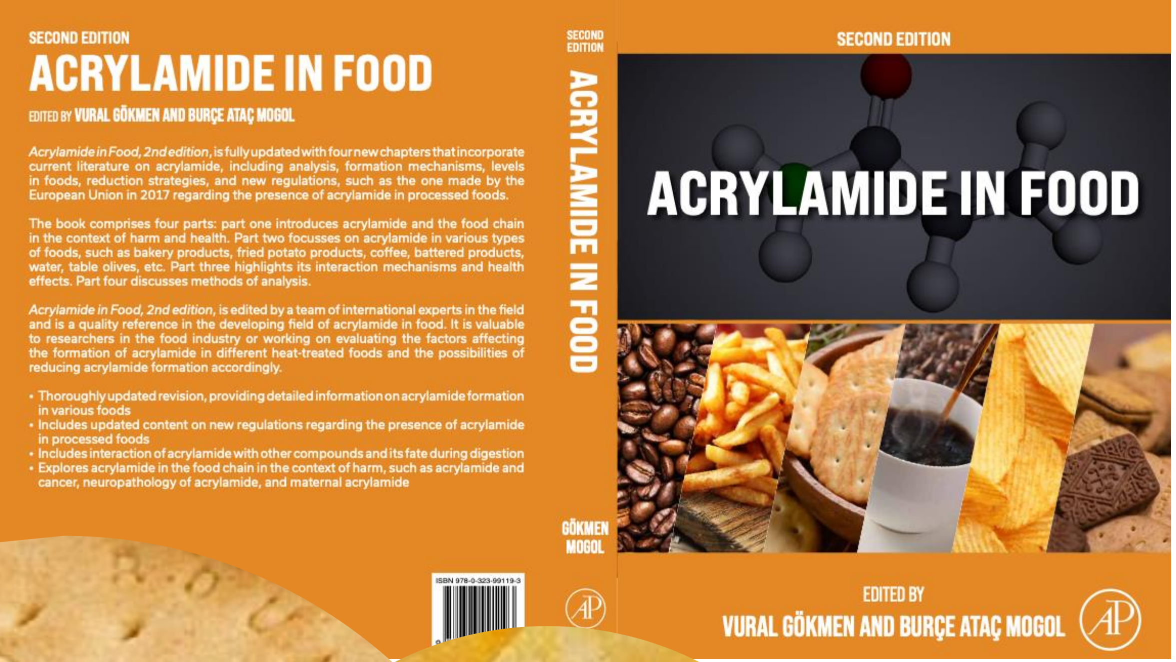


Figure
In vivo detoxification pathway of acrylamide in the presence of glutathione. Adapted from Kocadağlı and Gökmen, 2023
AAMA; N-acetyl-S-(2-carbamoylethyl)-L-cysteine
GAMA; N-(R, S)-acetyl-S-(2-carbamoyl-2-hydroxyethyl)-L-cysteine



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