Journal Pre-proof

Thermal Processing of Oilseeds: Multidimensional Impacts on Maillard Reaction Chemistry, Nutritional Safety, and Technological Innovations in Quality Control

Xinyu Li, Xinyue Liu, Zhiqiang Kong, Lin Li, Long Li, Marie-Laure Fauconnier, Minmin Li

PII: S0924-2244(25)00240-7

DOI: https://doi.org/10.1016/j.tifs.2025.105104

Reference: TIFS 105104

To appear in: *Trends in Food Science & Technology*

Received Date: 18 March 2025

Revised Date: 10 May 2025

Accepted Date: 23 May 2025

Please cite this article as: Li, X., Liu, X., Kong, Z., Li, L., Li, L., Fauconnier, M.-L., Li, M., Thermal Processing of Oilseeds: Multidimensional Impacts on Maillard Reaction Chemistry, Nutritional Safety, and Technological Innovations in Quality Control, *Trends in Food Science & Technology*, https://doi.org/10.1016/j.tifs.2025.105104.

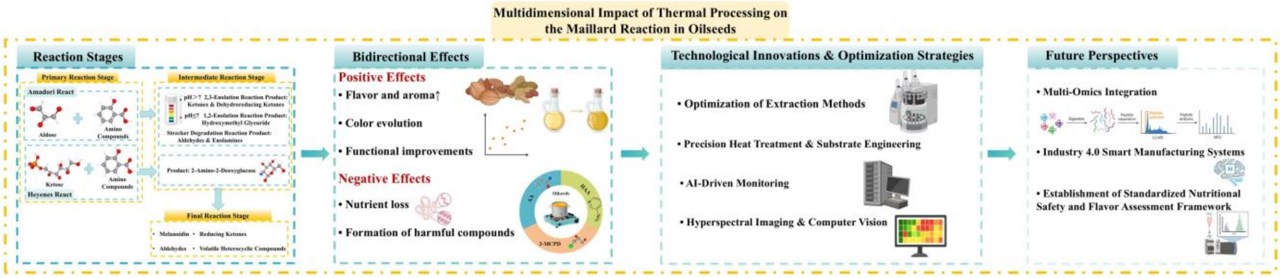
Abstract

Background: Oilseeds are essential global food resources, frequently subjected to thermal processing to enhance functionality and shelf stability. However, these thermal treatments trigger complex biochemical cascades, notably the Maillard reaction, which significantly impacts the nutritional and sensory properties of oilseed-derived products. The formation of Maillard reaction products (MRPs) introduces both beneficial bioactive compounds and potentially harmful advanced glycation end-products (AGEs), necessitating a balanced processing approach.

Scope and approach: This review critically examines the interplay between thermal processing parameters and MRP evolution in oilseed matrices, emphasizing their implications for food quality. The study explores modern analytical approaches, including AI-driven predictive modeling and hyperspectral computer vision systems, for real-time monitoring of MRP formation kinetics and color changes during processing. Furthermore, the review discusses the dual impact of heat exposure on bioactive compound degradation and the generation of potentially harmful AGEs, such as acrylamide and 5-hydroxymethylfurfural.

Key findings: Progressive thermal exposure induces nonlinear degradation of heat-sensitive phytochemicals while promoting AGE formation, highlighting the need for precision thermal engineering. Optimized processing conditions—temperatures below 140°C with dwell times under 30 minutes—are recommended to balance bioactive retention and mitigate MRP-associated risks. Emerging machine learning techniques and computer vision-enhanced automation present opportunities for next-generation smart processing frameworks. These advancements lay the foundation for nutritionally optimized oilseed products by intelligently modulating Maillard reaction pathways while addressing key food safety concerns in lipid-rich matrices.

Keywords: Oilseed matrices, Thermal processing; Maillard reaction chemistry; Nutritional safety; Smart processing technologies


Multidimensional Impact of Thermal Processing on the Maillard Reaction in Oilseeds
Reaction Stages
Primary Reaction Stage
Amadori React
Aldose
Amino Compounds
Ketose
Amino Compounds
Heyenes React
Intermediate Reaction Stage
pH>7 2,3-Enolation Reaction Product: Ketones & Dehydroreducing Ketones
pH≤7 1,2-Enolation Reaction Product: Hydroxymethyl Glyceride
Strecker Degradation Reaction Product: Aldehydes & Enolamines
Product: 2-Amino-2-Deoxyglucose
Final Reaction Stage
• Melanoidin • Reducing Ketones
• Aldehydes • Volatile Heterocyclic Compounds
Bidirectional Effects
Positive Effects
• Flavor and aroma↑
• Color evolution
• Functional improvements
Negative Effects
• Nutrient loss
• Formation of harmful compounds
Oilseeds
3-MCPD
Technological Innovations & Optimization Strategies
• Optimization of Extraction Methods
• Precision Heat Treatment & Substrate Engineering
• AI-Driven Monitoring
• Hyperspectral Imaging & Computer Vision
Future Perspectives
• Multi-Omics Integration
• Industry 4.0 Smart Manufacturing Systems
• Establishment of Standardized Nutritional Safety and Flavor Assessment Framework

Thermal Processing of Oilseeds: Multidimensional Impacts on Maillard Reaction Chemistry, Nutritional Safety, and Technological Innovations in Quality Control

Xinyu Li[a,b,1], Xinyue Liu[a,1], Zhiqiang Kong[c], Lin Li[a], Long Li[a], Marie-Laure.Fauconnier[d], Minmin Li[a*]

[a] Institute of Food Science and Technology, Chinese Academy of Agricultural Sciences/Key Laboratory of Agro-products Quality and Safety Control in Storage and Transport Process/Laboratory of Agro-products Quality Safety Risk Assessment, Ministry of Agriculture and Rural Affairs, Beijing 100193, P. R. China

[b] Food Science College, Shenyang Agricultural University, Shenyang 110866, China

[c] State Key Laboratory for Biology of Plant Diseases and Insect Pests, Institute of Plant Protection, Chinese Academy of Agricultural Sciences, Beijing 100193, P. R. China

[d] Chemistry of Natural Molecules , Gembloux Agro-Bio-Tech, University of Liège, Passage des Déportés 2, b-5030 Gembloux, Belgium

[*]Corresponding author.

E-mail address: liminmin@caas.cn (M.Li)

[1] These authors contributed equally to this paper.

1.Introduction

Global oilseed production—dominated by soybean, rapeseed, and sunflower seeds—exceeds 138.6 million metric tons annually, underpinning a multibillion-dollar edible oil industry (Wei et al., 2025). Thermal processing is a cornerstone technique in oilseed manufacturing, designed to optimize oil yield, enhance sensory attributes, and ensure microbial safety. However, its multifaceted impact extends beyond simple physical and biochemical modifications, profoundly influencing the complex network of Maillard reaction (MR) pathways. The MR, a non-enzymatic glycation reaction between reducing sugars and amino compounds, governs critical quality attributes such as color development, flavor evolution, and antioxidant activity in lipid-rich matrices (Huang et al., 2023; Y. Zhang et al., 2021). Despite its industrial significance, the nuanced interplay between thermal exposure, MR progression, and oilseed-specific reactivity remains underexplored, warranting an integrated investigation into the technological, nutritional, and safety dimensions of this process.

Conventional thermal treatments, including roasting, infrared radiation, and microwave-assisted heating, operate within diverse thermal regimes (60-200℃), each modulating MR kinetics uniquely. At moderate temperatures (<140℃, beneficial melanoidins and bioactive compounds accumulate, improving oxidative stability and imparting desirable roasted flavors. However, excessive heat exposure (>160℃) induces the formation of potentially harmful advanced glycation end-products (AGEs) such as acrylamide (AA) and 5-hydroxymethylfurfural (5-HMF), raising significant nutritional safety concerns (Z. Cai et al., 2021; Cha & Lee, 2020). This duality presents an unresolved processing paradox: how can industry optimize oilseed processing to maximize desirable functionalities while mitigating detrimental consequences?

The MR, a non-enzymatic glycation cascade between reducing sugars and amino compounds, governs critical quality attributes in lipid-protein matrices, including color evolution, antioxidant capacity, and flavor development (Pucci et al., 2024). However, reaction kinetics in oilseeds remain poorly quantified, with conflicting reports on phytochemical degradation thresholds and AGE formation dynamics under varying moisture (5-15% w/w) and pH (4.5-8.0) conditions (D. Yang et al., 2025). Current limitations in real-time monitoring of intermediate Maillard reaction products (MRPs) (e.g., Amadori products, dicarbonyls) further hinder process optimization, necessitating advanced analytical frameworks. Emerging smart technologies-artificial intelligence (AI)-druned predictive modeling and hyperspectral computer vision-offer transformative potential for resolving these challenges. AI algorithms enable multi-parametric optimization of thermal thresholds (<140℃) and dwell times (<30 min) to mitigate AA formation while preserving tocopherols and phenolic acids. Concurrently, computer vision systems achieve non-destructive quantification of browning indices ($\Delta E > 15$) and MRPs patial distribution, bridging the gap between laboratory-scale insights and industrial scalability (W. Zhang et al., 2020).

This review critically synthesizes advances in MRPs characterization, mechanistic modeling, and intelligent process control, addressing three underexplored dimensions: Reaction phase mapping: Kinetic profiling of early (Strecker aldehydes) vs. advanced (melanoidin polymerization) Maillard stages in lipid-rich matrices. Nutritional trade-offs: Quantifying nonlinear relationships between antioxidant enrichment (e.g., MRPs-derived radical scavengers) and AGE accumulation. Technological convergence: Integrating AI-guided process automation with spectroscopic quality assurance systems for sustainable oilseed valorization. By delineating these intersections, we provide a scientific foundation for next-generation oilseed processing strategies, harmonizing quality enhancement with food safety imperatives. The integration of Industry 4.0 solutions—including digital twin modeling and sensor-driven adaptive roasting—holds promise for developing nutritionally optimized oilseed-derived products.

2.The Chemical Mechanism of MR

The MR, a non-enzymatic browning process between reducing sugars and amino compounds, plays a dual role in oilseed processing: it enhances flavor and oxidative stability while posing risks of nutrient degradation and contaminant formation. Understanding its chemical intricacies is critical for optimizing thermal treatments in oilseed applications.

2.1 Manufacturing Pathways of Edible Oils from Oilseeds and the Role of Thermal Processing

The extraction of edible oils from oilseeds employs several fundamental techniques, including mechanical pressing (both hot and cold), solvent extraction, aqueous enzymatic extraction, and supercritical CO_2 extraction, all of which involve varying degrees of thermal processing. Hot pressing, frequently utilized for sesame, rapeseed, and peanut oil, entails a pre-roasting phase at temperatures ranging from 120 to 160°C. This process can enhance oil yield by 15 to 20% by disrupting cellular structures and initiating Maillard reactions (MR), which produce flavor-active compounds such as methylpyrazines and antioxidants. However, excessive heating may also lead to the formation of potentially harmful substances, including AA and 5-HMF (Kang & Suh, 2022; Lin & Grasso, 2025). Conversely, cold pressing, conducted at temperatures below 70°C, is more effective in preserving heat-sensitive bioactive compounds like tocopherols and polyphenols. Nevertheless, this method typically results in lower oil yields (65–75%) and produces oils with diminished flavor and oxidative stability (Lu et al., 2025).

To facilitate a comprehensive comparison of thermal methods, Figure 1 illustrates the effects of microwave treatment, roasting, hot air heating, and infrared heating on fourteen different oilseed varieties. These methods exhibit significant variations in their influence on physicochemical properties, minor lipid components, and oxidative stability. Notably, infrared heating has been shown to improve oil yield while reducing the formation of AA and HMF, and it retains a greater proportion of antioxidants compared to traditional roasting techniques. Although solvent extraction is highly efficient, achieving yields of up to 98%, it still involves thermal processes such as toasting and desolventizing, typically conducted at temperatures exceeding 100°C. These steps necessitate careful monitoring to prevent excessive oxidation or the accumulation of MR products (Carré et al., 2025; L. Jiang et al., 2025). Aqueous enzymatic extraction, performed at temperatures between 40 and 60°C, along with supercritical CO_2 extraction (conducted at 30–60°C and 10–20 MPa), minimizes thermal degradation, although the latter may require subsequent treatment to achieve the desired roasted aroma (Allay et al., 2025).

In conclusion, thermal processing serves a dual function in oil production, facilitating both extraction and flavor development while simultaneously posing potential risks to safety and quality. As depicted in Figure 1, the selection of extraction methods and the regulation of temperature must be customized to the specific types of oilseeds and processing objectives in order to optimize product performance.

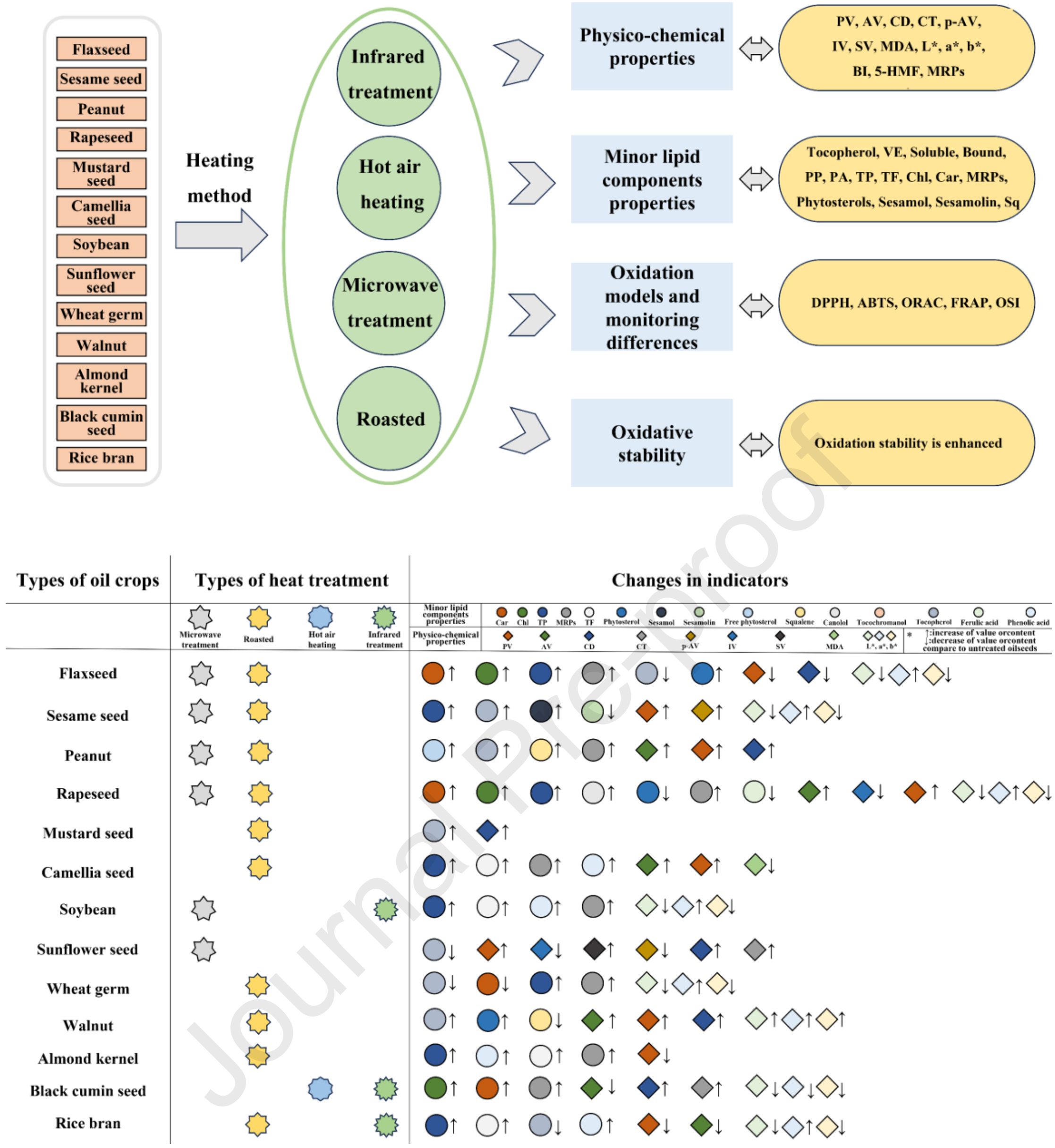


Figure 1 Thermal Processing Effects on Oilseed Quality Attributes and Antioxidant Stability

Note: PV : Peroxides Value; AV : Acid Value; CD : Conjugated Dienes; CT : Conjugated Trienes; p-AV : p-Anisidine Value; IV : Iodine Value; SV : Saponification Value; MDA : Malondialdehyde; L* : Darkness to Lightness; a* : Redness to Greenness; b* : Yellowness to Blueness; BI : Browning Index; 5-HMF : 5-Hydroxymethylfurfural; MRPs : Maillard Reaction Products; VE: Vitamin; PP: Polyphenol; PA: Phenolic Acid; TP: Total Phenolic; TF: Total Flavonoid; Chl: Chlorophyll; Car: Carotenoid; Sq: Squalene; DPPH: 2,2-Diphenyl-1-picrylhydrazyl Radical Scavenging; ABTS: 2,2'-Azinobis(3-ethylbenzothiazoline-6-sulfonic acid) Radical Scavenging; ORAC: Oxygen Radical Absorbance Capacity; FRAP: Ferric Reducing Antioxidant Power; OSI: Oxidative Stability Index

2.2 Thermal Processing as a Critical Lever in Oilseed Functionality

Thermal pretreatment is a critical step in the processing of oilseeds, particularly in the production of soybean oil. Various methods, including baking at temperatures ranging from 120 to 180°C, microwave irradiation at a frequency of 2.45 GHz, and infrared radiation with wavelengths between 3 and 10 μm, significantly influence both oil extraction efficiency and flavor characteristics. A systematic comparison of these techniques indicates notable differences in efficiency and safety outcomes. For instance, dry roasting at 160°C for 15 minutes can enhance oil yield by approximately 12% compared to untreated seeds; however, this method also leads to the formation of AA at levels reaching 420 μg/kg. In contrast, infrared heating at 140°C for 10 minutes results in a 9% increase in oil yield while restricting AA formation to below 80 μg/kg. Additionally, the retention of antioxidants varies significantly, with γ-tocopherol retention exceeding 85% when using infrared heating, compared to only 60% retention with conventional roasting methods. The browning index (ΔE) values also differ markedly, as infrared-treated samples exhibit moderate color changes (ΔE ~7.5), whereas samples subjected to roasting display pronounced browning (ΔE >12).

These quantitative differences highlight the inherent trade-offs between flavor, yield, and the formation of contaminants across various thermal processing techniques. These treatments reduce oil viscosity by 30-50%, facilitating the release of high-melting-point fatty acids (e.g., palmitic acid, Tm = 63°C) while preserving fatty acid composition integrity(Z. Cai et al., 2021). The reduction in viscosity is attributed to the disruption of cellular structures and lipid-protein complexes, enabling easier separation of oil bodies during mechanical pressing. Crucially, controlled thermal regimes (100-200°C) activate Maillard cascades, generating melanoidins that enhance oxidative stability (peroxide value reduction by 20-40%) and impart nutty/roasted flavors via Strecker aldehydes (Y. Zhang et al., 2021). For instance, methylpyrazine and furfuryl alcohol-key contributors to roasted aromas-are synthesized when oilseeds are heated above 140°C. However, excessive heating (>160°C, >30 min) triggers nutrient degradation (e.g., 50% tocopherol loss) and neo-formed contaminants like AA (up to 450 μg/kg in roasted peanuts), necessitating precision thermal engineering (Alsafra et al., 2023). Recent studies highlight the role of time-temperature integrators (TTIs) such as furosine, which quantifies heat exposure by tracking lysine modification in Amadori products (Nie et al., 2022).

2.3 Reaction Kinetics: A Triphasic Framework

The MR in oilseeds follows a triphasic trajectory (Figure 2), influenced by the lipid-protein matrix's unique physicochemical properties: Initial Phase (0-10 min at 120°C): Reducing sugars (e.g., glucose, fructose) condense with free amino acids (e.g., lysine, arginine) to form Schiff bases, which undergo Amadori rearrangement to yield 1-amino-1-deoxy-2-ketose derivatives. These colorless intermediates act as reservoirs for subsequent flavor volatiles. In oilseeds, phospholipids in cell membranes catalyze this step by stabilizing transition states through hydrophobic interactions (Du et al., 2024).

Intermediate Phase (10-30 min at 140-160℃): Amadori products follow pH-dependent pathways: Acidic conditions (pH 4-6): 1,2-Enolization dominates, producing 5-HMF (50-200 mg/kg in baked oilseeds), which further reacts with amino acids to form melanoidin precursors. Alkaline conditions (pH 8-9): 2,3-Enolization generates reductones and dehydroreductones, which act as radical scavengers. Strecker degradation: α-Dicarbonyls (e.g., methylglyoxal) react with amino acids, releasing CO_2 and producing aldehydes (e.g., 2-methylpropanal) and heterocyclic compounds like pyrazines (Nomi et al., 2025). Notably, lipid oxidation byproducts (e.g., malondialdehyde) may cross-react with Maillard intermediates, forming unique adducts such as aldehyde-Schiff base complexes. Terminal Phase (>30 min at >160℃): Reactive intermediates (furanoids, pyrroles) polymerize into melanoidins (M_W > 10 kDa), contributing to browning (ΔE > 15) and antioxidant activity. However, in oilseeds, melanoidin formation competes with lipid oxidation pathways. For example, unsaturated fatty acids (e.g., linoleic acid) may quench reactive carbonyls, altering polymerization kinetics (Valle-Sánchez et al., 2025).

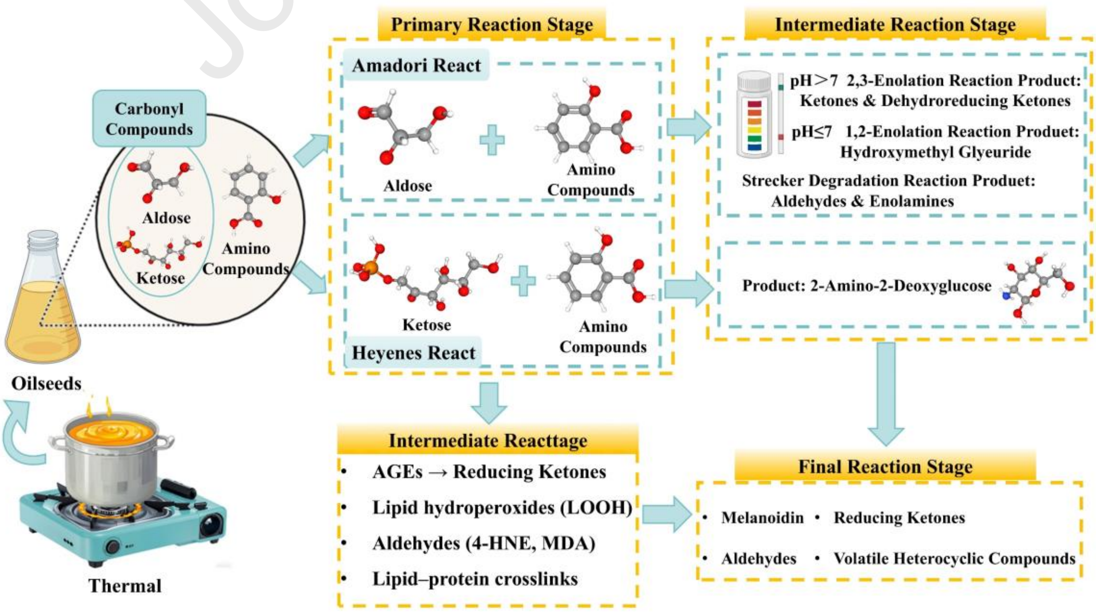


Figure 2 Triphasic Maillard Reaction Mechanisms with Lipid–Protein Matrix-Specific Intermediates in Oilseed Systems

2.4 Multifactorial Modulation of Maillard Outcomes

Key determinants of reaction trajectories include: Reducing Sugar Specificity: Pentoses (ribose) react 5× faster than hexoses (glucose), accelerating 5-HMF formation (Wang et al., 2024). In soybeans, endogenous raffinose family oligosaccharides (RFOs) undergo hydrolysis during roasting, releasing galactose and glucose to fuel Maillard pathways. Amino Compound Hierarchy: Low-MW peptides (<3 kDa) enhance volatile yield by 40% versus intact proteins due to increased accessibility of ε-amino groups (Sun et al., 2022). Glutamine and asparagine (Asn) are critical precursors for AA, which peaks at 160°C/25 min (Bachir et al., 2022). The pathway for AA formation transpires concurrently with the synthesis of aroma-active compounds. In particular, the MR involving reducing sugars (such as glucose and fructose) and amino acids results in the production of AA through the intermediate 3-aminopropionamide (3-APA). Additionally, this reaction yields volatile compounds, including pyrazines and Strecker aldehydes, which contribute to the characteristic roasted flavor. Consequently, the formation of AA and flavor molecules is interconnected, as they share common precursors and thermal conditions within oilseed roasting processes (Bachir et al., 2022; Shi et al., 2024; Sun et al., 2022). Moisture Modulation: Optimal water activity (aw 0.6-0.7) maximizes MRPs diversity by balancing reactant mobility and hydrolysis. At aw < 0.4, limited molecular diffusion inhibits AA by 40% but restricts flavor development (Shi et al., 2024). Specifically, moisture content serves a dual function in influencing both beneficial and detrimental Maillard products. At intermediate levels of water activity (approximately 0.6), molecular mobility is enhanced without excessive dilution, thereby fostering the production of flavor volatiles and antioxidant-active melanoidins. In contrast, at very low water activity levels (below 0.3), the formation of AA is promoted due to heightened thermal concentration effects and diminished hydrolysis of sugar-asparagine adducts. Therefore, precise regulation of moisture conditions is crucial for encouraging the formation of desirable MRPs while mitigating the presence of undesirable contaminants such as AA and 5-HMF. Thermal Method Selection: Wet thermal methods (e.g., steaming) preserve 80-90% of tocopherols but limit Maillard-derived flavors. Conversely, dry roasting (140-160°C) elevates AGEs like carboxymethyllysine (Nie et al., 2022).

Importantly, the factors governing Maillard outcomes—such as moisture level, reducing sugar type, amino acid composition, and thermal modality—do not act independently but are frequently co-optimized in practical processing. For example, thermal method selection (e.g., infrared vs. microwave) influences internal moisture distribution, which in turn alters reaction kinetics and intermediate diffusion. Therefore, a comprehensive understanding of Maillard modulation requires not only single-factor analysis but also multi-variable synergy evaluation, as applied in predictive modeling and intelligent process design.

2.5 Oilseed-Specific Reactivity: Antioxidant-Degradation Paradox

Oilseed matrices uniquely harbor antioxidants that interact with Maillard chemistry (Figure 3): Polyphenols: Thermal processing (140°C/15 min) degrades 30% of free phenolics but releases bound forms (e.g., ferulic acid ↑20%) via ester bond cleavage, improving oxidative stability (IP values ↑2 h) (Z. Cai et al., 2021). Tocopherols: Baking (160°C/10 min) reduces α-tocopherol by 50%, yet δ-tocopherol regenerates (↑15%) via redox cycling with Maillard-derived reductones (W. Zhang et al., 2020). Phytosterols: Heating at 140 °C for 5 min disrupts oilseed cell membranes and pigment–protein bonds, facilitating the release of phytosterols (campesterol ↑3.6%, sitosterol ↑5.9%), tocopherols, and pigments that enhance oil's oxidative stability. Paradoxically, melanoidins synergize with residual antioxidants, scavenging 60-80% of DPPH radicals in roasted oils. Proposed mechanisms include electron transfer from phenolic hydroxyl groups to melanoidin conjugated systems, though structural characterization remains challenging (Li et al., 2020).

The MR in oilseeds represents a delicate equilibrium between flavor enhancement and nutritional preservation. Advances in precision thermal engineering-such as pulsed electric field-assisted heating and AI-driven temperature control-are poised to optimize this balance. Future research must resolve mechanistic ambiguities, particularly melanoidin-antioxidant synergies and lipid-Maillard cross-talk, to unlock novel functionalities in plant-based oils.

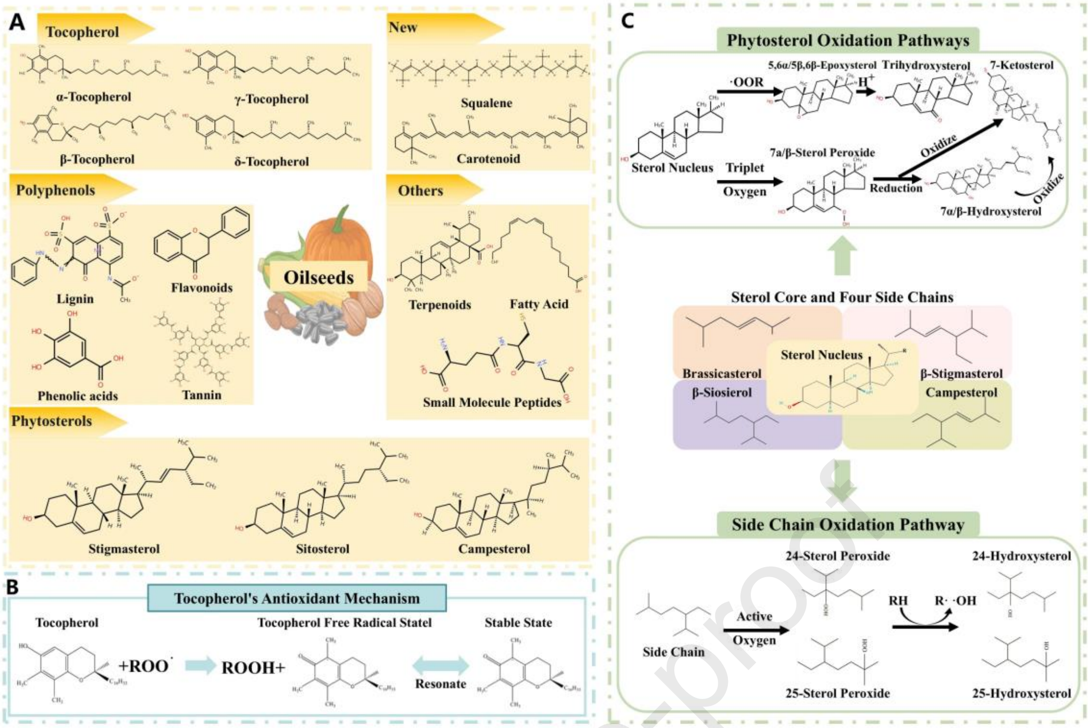


Figure 3 (A) Bioactive compound classification; (B) Tocopherol's Antioxidant Mechanism; (C) Phytosterol oxidation pathways

3. The multiple effects related to the Maillard reaction in oilseeds

The MR in oilseeds manifests as a complex interplay of beneficial and detrimental outcomes, governed by thermal processing parameters. Sensory enhancements arise from volatile heterocycles (e.g., 2,5-dimethylpyrazine, OAV >10) (X. Xie et al., 2025) and chromatic evolution (ΔE >5) (Shi et al., 2024), with infrared-treated soybeans showing a* shifts from −2.98 to +3.99 due to melanoidin polymerization (5-HMF: 34.97 μg/g). Concurrently, melanoidins (>10 kDa) confer antioxidant benefits via Fe^{2+} chelation (Kd = $10^{-}6$ M) and angiotensin-converting enzyme (ACE) inhibition (IC_{50} = 1.2 mg/mL), yet compromise lysine bioavailability by 30–50% through ε-amino glycation and reduce iron absorption by 25% via insoluble Fe^{3+}-melanoidin complexes. Conversely, excessive heating (>150°C) triggers contaminant genesis: AA forms via asparagine-glucose decarboxylation (450 μg/kg in peanuts at 160°C), while 1-methyl-6-phenylimidazo [4,5-b]-pyridine (PhIP) emerges from tryptophan pyrolysis (2–5 ng/g in fried oils) and 3-monochloropropane-1,2-diol or 3-chloropropane-1,2-diol (3-MCPD) esters (0.1–2.5 mg/kg) nucleate via chloride-catalyzed esterification. Mitigation strategies—such as chloride sequestration (80% reduction via $CaCO_3$) and sugar-asparagine ratio control (<0.5 mol/mol)—highlight the need to balance flavor, functionality, and safety in oilseed thermal engineering (Y. Zhang et al., 2021).

3.1 Flavor-Aroma Synergy and Chromatic Evolution

The MR drives critical sensory transformations in oilseeds, balancing flavor enhancement with color development. Volatile profiling of heat-processed oils reveals a dynamic shift: unbaked oils are dominated by aldehydes (hexanal, nonanal) and alcohols, contributing grassy/green notes, while thermal treatment (>120℃) induces heterocyclic compound formation-pyrazines (nutty), furans (caramel), and pyrroles (earthy)-imparting roasted complexity (H. Yang et al., 2024). Gas chromatography-olfactometry identifies 2,5-dimethylpyrazine and 2-acetyl-1-pyrroline as key odorants (odor activity values >10), defining oil aroma profiles (Qiu et al., 2025). Concurrently, chromatic shifts (ΔE >5) correlate with advanced Maillard stages. Infrared-treated soybeans (140℃/100 s) exhibit a* (redness) increases from -2.98 to +3.99 and L* (lightness) reductions from 62.58 to 61.68, paralleling melanoidin accumulation (5-HMF: 34.97 μg/g) and AA formation (69.49 ng/g) (Figure 4). These changes align with melanoidin polymerization (M_W >5 kDa), though structural heterogeneity (e.g., cross-linked polyphenol-protein complexes) complicates characterization (Guo et al., 2022). Crucially, melanoidins demonstrate dose-dependent bioactivity: at 0.1-1 mg/mL, they scavenge 60-80% of DPPH radicals but induce pro-inflammatory responses at >5 mg/mL, necessitating process optimization (Jia et al., 2023). The comparative data in Figure 4 illustrate that infrared heating offers a milder MR trajectory than microwave roasting, with lower ΔE values and reduced contaminant generation, confirming its potential as a safer alternative. Compared to traditional roasting methods at 160℃ for 15 minutes—which yield AA concentrations of 420–450 μg/kg and 5-HMF levels exceeding 60 μg/g—soybeans treated with infrared heating at 140℃ for 100 seconds show significantly lower AA levels (69.49 ng/g) and moderate 5-HMF concentrations (34.97 μg/g), indicating a more advantageous balance between safety and flavor.

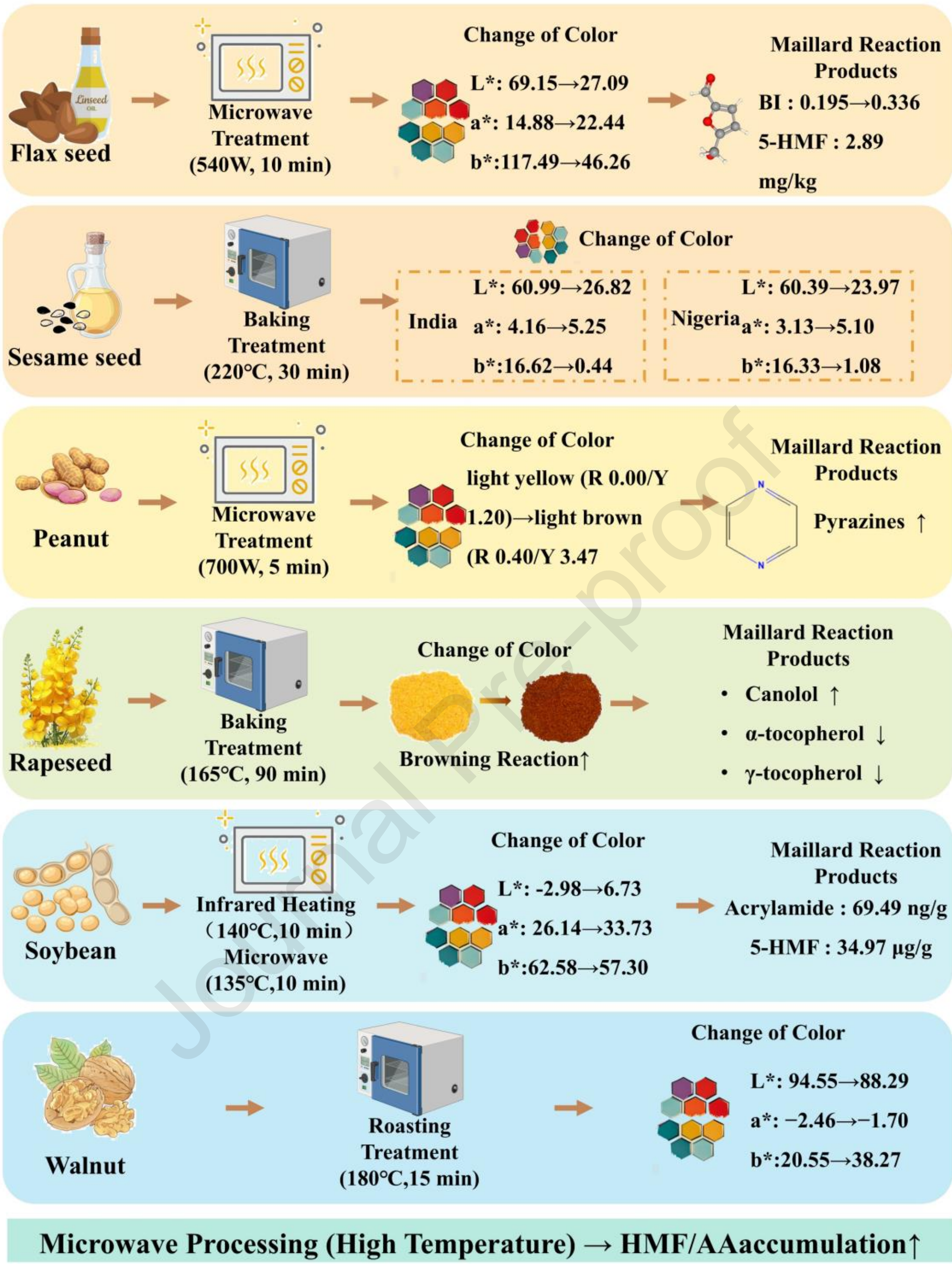


Figure 4 Quantified Chromatic and MRPs Changes Across Thermal Modalities (Infrared vs. Microwave)

Note: L*, lightness from 0 (dark) to 100 (light); a*, redness from −a (green) to +a (red); b*, yellowness from −b (blue) to +b (yellow), BI : Browning index; 5-HMF : 5-Hydroxymethylfurfural.

3.2 Biofunctional Trade-offs: Antioxidant Gains vs. Nutrient Losses

The MR in oilseeds orchestrates a biochemical paradox, simultaneously generating bioactive compounds with health-promoting properties while compromising nutritional integrity. Antioxidant synergy arises from melanoidins, high-molecular-weight polymers (>10 kDa) that exhibit multifaceted radical-quenching mechanisms. These include Fe^{2+} chelation (Kd = 10^{-6} M) and hydroxyl radical scavenging (IC_{50} = 0.8 mg/mL), synergizing with residual tocopherols to reduce peroxide values (PV) by 40–60% in roasted sunflower oil (Ke & Li, 2023).

Notably, the increase in δ-tocopherol (↑15%) observed during moderate roasting may be explained by a redox recycling mechanism facilitated by reductones derived from the MR. In this mechanism, δ-tocopherol functions as a hydrogen donor to neutralize lipid peroxyl radicals (LOO•), resulting in the formation of a δ-tocopheroxyl radical (δ-T•). Subsequently, intermediate products of the MR, such as 3-deoxyglucosone and maltol, which possess significant reducing capabilities, can regenerate δ-tocopherol by donating electrons or hydrogen atoms to δ-T• (Bork et al., 2023). This two-step redox cycle can be summarized as follows:

δ-Tocopherol + LOO• → δ-T• + LOOH

δ-T• + Reductone → δ-Tocopherol + Oxidized Reductone

The regeneration process is thermodynamically favorable, with a Gibbs free energy change (ΔG°) estimated to be between −20 to −30 kJ/mol. Additionally, this process may be further stabilized by melanoidin conjugates that act as electron mediators (Bolchini et al., 2025). These interactions are crucial for maintaining tocopherol levels and enhancing oxidative stability, particularly in low-moisture oilseed systems where the pressure of lipid oxidation is elevated. Concurrently, antihypertensive activity manifests in high-MW melanoidins (>50 kDa) that competitively inhibit ACE by binding Zn^{2+} at its catalytic site (IC_{50} = 1.2 mg/mL), demonstrated in spontaneously hypertensive rats showing 15 mmHg systolic blood pressure reduction after 8-week dietary intervention (Rufián-Henares & Morales, 2007; P. Zhao et al., 2025).

However, these benefits come at a nutritional cost. Lysine bioavailability declines by 30–50% due to ε-amino group glycation, as quantified via OPA-FMOC assays in glycated soy protein isolates. Circular dichroism (CD) spectroscopy further reveals that glycation increases random coil content by 15–20% in peanut proteins, enhancing emulsification capacity (oil-binding ↑35%) but reducing pepsin digestibility (↓40%) due to steric hindrance (Zou et al., 2025). Mineral absorption is similarly compromised: Fe^{3+}-melanoidin complexes reduce iron uptake by 25% in Caco-2 cell models, attributed to insoluble aggregate formation in intestinal lumen (ALjahdali & Carbonero, 2019). These trade-offs underscore the need for precision processing to balance MRPs bioactivity with nutrient preservation (Figure 5).

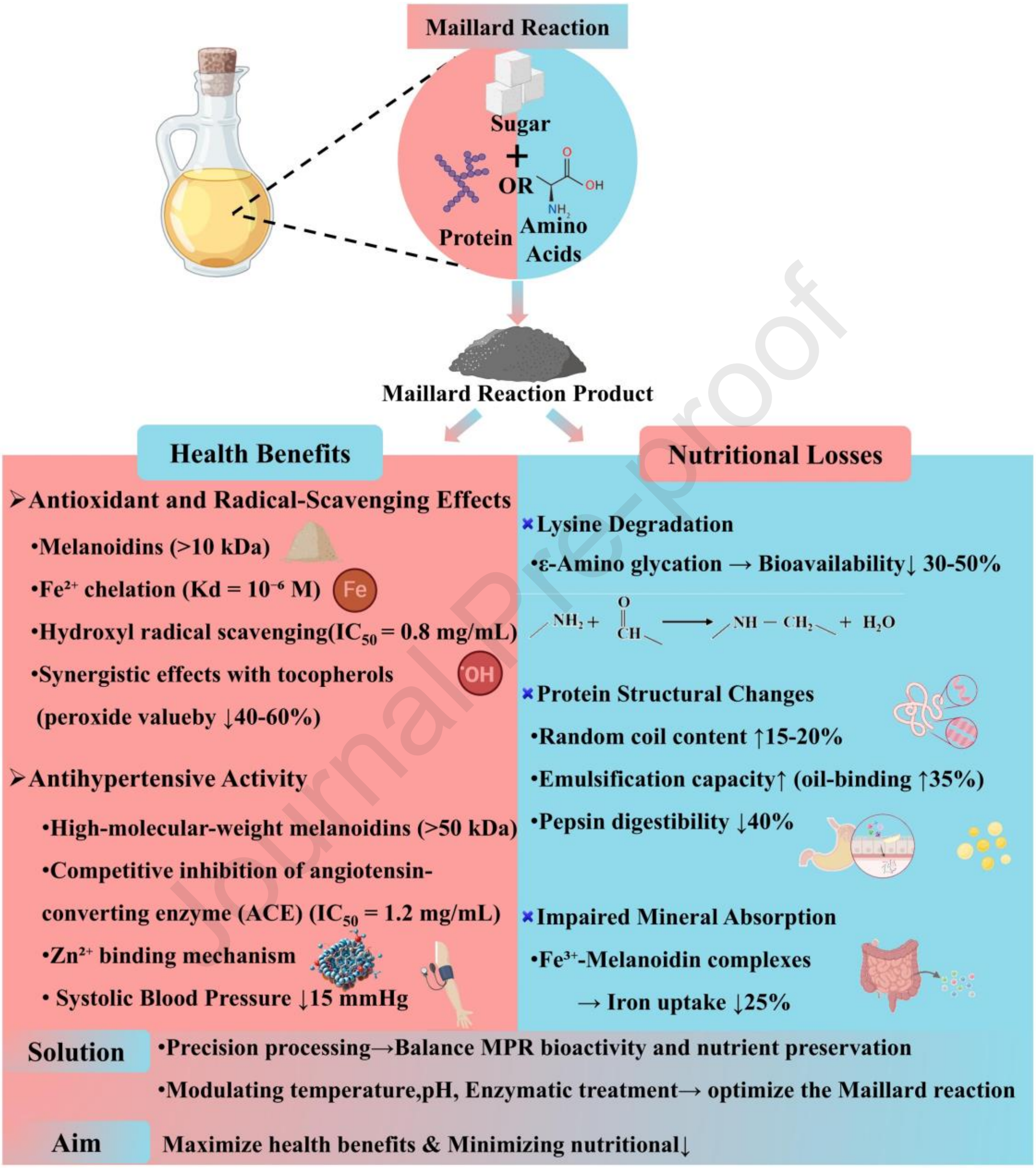


Figure 5 Antioxidant and Antihypertensive Actions of MRPs

3.3 Contaminant Genesis: Thermal Processing as a Double-Edged Sword

The thermal processing of oilseeds enhances their functional properties; however, it also inadvertently promotes the formation of toxicologically significant contaminants when critical temperature-time thresholds are surpassed. The temperature of 150°C is often cited as a general threshold, supported by various lines of evidence. For example, the formation of AA in oil-rich matrices, such as peanuts, increases significantly above 150°C, with peak concentrations occurring between 160 and 180°C (Fan et al., 2023). Additionally, the formation rates of 5-HMF and 3-MCPD esters exhibit exponential increases beyond this temperature (Hu et al., 2021; Yıldız et al., 2024). Consequently, 150°C is recognized as a practical inflection point that strikes a balance between adequate thermal activation for flavor enhancement and a substantial rise in the risk of contaminant formation. Nonetheless, this threshold may be influenced by factors such as the composition of the matrix, pH levels, and moisture content. The newly formed compounds—specifically AA, HAAs, AGEs, and 3-MCPD esters—present regulatory challenges and require a comprehensive mechanistic understanding for effective mitigation (see Figure 6).

It is crucial to recognize that the pathways leading to the formation of these contaminants are interconnected and, at times, may compete with the MR cascade that is responsible for flavor development and the enhancement of antioxidant properties. For instance, AA and HAAs utilize asparagine and tryptophan as shared precursors alongside aroma-active compounds such as Strecker aldehydes and pyrazines. The transition from early Maillard intermediates, such as Amadori products, to advanced-stage polymers, known as melanoidins, can either hinder or facilitate the formation of beneficial antioxidants or genotoxic byproducts, contingent upon the intensity of thermal treatment and the composition of the food matrix. This chemical interaction highlights a complex trade-off: the same conditions that improve the aroma and oxidative stability of oils may simultaneously encourage the production of deleterious substances, unless carefully regulated.

In response to feedback from reviewers, Figure 6 has been revised to enhance the clarity of the selection criteria and the structure of the information presented. The figure now standardizes three critical dimensions for each contaminant: (i) pathways of formation, (ii) influencing factors (such as temperature, precursors, pH, and moisture), and (iii) toxicity profiles (including genotoxicity and No Observed Adverse Effect Levels, NOAELs). Additionally, toxicity information for AA has been included, along with the influencing factors for HAAs. Furthermore, AGEs, which were prominently referenced in both the abstract and introduction, have been integrated into the figure to ensure consistency throughout the manuscript. These revisions are intended to enhance visual clarity, completeness of information, and logical coherence across the various sections.

AA: The Maillard Liability. AA arises dominantly through the decarboxylative condensation of Asn with reducing sugars (e.g., glucose), following pseudo-first-order kinetics (Ea = 120 kJ/mol). Under roasting conditions (160°C/25 min), AA concentrations escalate sigmoidally, peaking at 450 μg/kg in peanuts, with critical thresholds at moisture <5% (limiting hydrolysis) and pH >7.0 (favoring deprotonated Asn intermediates). Isotopic tracer studies reveal competing pathways: At 180°C, over 60% of AA originates from lipid oxidation-derived acrolein reacting with ammonia, bypassing classical Maillard routes (Hidalgo & Zamora, 2023). This dual-origin mechanism complicates mitigation, requiring simultaneous control of sugar-Asn ratios (<0.5 mol/mol) and polyunsaturated fatty acid content (<15% w/w).

HAAs: Protein Pyrolysis Byproducts. HAAs, notably 2-amino-1-methyl-6-phenylimidazo-[4,5-b]-pyridine (PhIP), form via free radical-mediated pyrolysis of tryptophan/creatinine complexes at oil-water interfaces (≥170°C). LC-MS/MS quantification demonstrates HAAs accumulation in fried oils (2–5 ng/g PhIP) correlates exponentially with surface temperature (R^2 = 0.94) and tryptophan availability (>1.2 mg/g matrix). Crucially, HAAs require metabolic activation via hepatic CYP1A2-mediated N-hydroxylation to exert genotoxicity, a process amplified by lipid peroxidation products (e.g., 4-hydroxynonenal) through Ah receptor upregulation.

3-MCPD Esters: Chloride-Catalyzed Hazards. In chloride-rich oilseeds (≥50 ppm), thermal esterification of diacylglycerols at 180°C generates 3-MCPD esters (0.1–2.5 mg/kg in palm oil), with formation rates tripling per 10°C increment (Q10 = 3.1). In vivo toxicokinetics reveal intestinal lipase-mediated hydrolysis releases free 3-MCPD, inducing renal tubular hyperplasia in rats (NOAEL = 0.3 mg/kg bw/day). Chloride sequestration strategies using calcium carbonate (1% w/w) reduce ester yields by 80% through precipitation of Cl^- ions as $CaCl_2$, though this risk altering oil crystallization behavior (Ji et al., 2023).

AGEs: Trade-offs Arising from Glycation. AGEs, including Nε-(carboxymethyl)lysine (CML) and Nε-(carboxyethyl)lysine (CEL), primarily arise from the oxidative degradation of Amadori intermediates or from the reaction of lipid-derived carbonyl compounds with lysine residues during extended or excessive heating (exceeding 140 °C). In thermally processed oilseeds, the concurrent presence of reducing sugars (such as glucose and galactose) and lysine-rich proteins often leads to the formation of AGEs alongside late-stage MRPs like melanoidins.

This simultaneous occurrence indicates a biochemical competition between antioxidant polymerization pathways and detrimental glycation processes. For example, when dicarbonyl compounds, such as methylglyoxal, are neutralized by polyphenol-derived reductones or are involved in melanoidin synthesis, the accumulation of AGEs is mitigated. Conversely, under oxidative conditions or within lipid-rich environments, these same dicarbonyls may preferentially react with lysine, resulting in increased AGE formation. This duality renders the formation of AGEs particularly sensitive to the redox environment, the availability of precursors, and the extent of thermal exposure. While certain AGEs are associated with pro-inflammatory and pro-oxidant effects in vivo, some AGE-modified peptides may exhibit moderate antioxidant activity or emulsifying properties in vitro (Twarda-Clapa et al., 2022). Consequently, AGEs in oilseed systems illustrate the nutritional complexity inherent in the MR continuum, wherein functionality and toxicity can arise from intersecting chemical pathways.

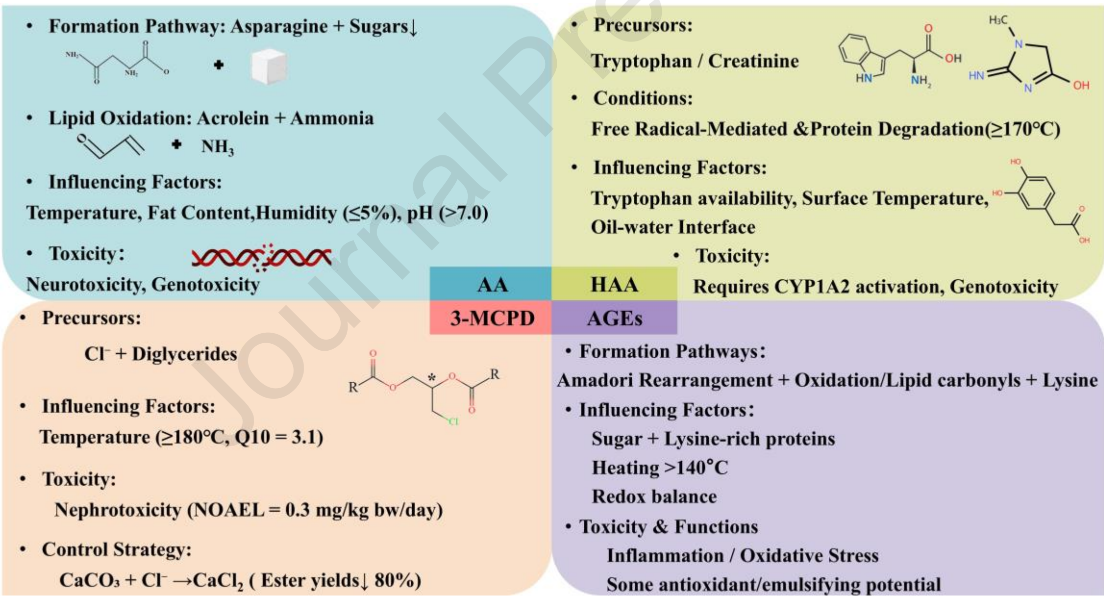


Figure 6 Contaminant Formation Pathways and Mitigation Levers in Thermally Processed Oilseeds, Highlighting Critical Control Points for AA, HAAs, 3-MCPD, and AGEs Esters

4: Technological Frontiers in Maillard Reaction Management

4.1 Extraction Modalities: Balancing Yield and MRPs Integrity

The extraction methodology employed in oilseed processing profoundly impacts both MRPs profiles and oil quality, necessitating a strategic balance between yield optimization and bioactive preservation (Z. Cai et al., 2025). Cold pressing (<70°C) retains 80-90% of heat-sensitive MRPs such as early-stage Amadori products and Strecker aldehydes, which contribute to nutty flavor precursors. However, its limited oil recovery (≤65%) stems from unruptured parenchyma cells retaining bound lipids, as observed in unroasted sesame seeds (J. Yang et al., 2021). In contrast, solvent extraction (hexane/ethanol, 6:4 v/v) achieves near-complete oil recovery (95-98%) but exhibits selectivity: hydrophobic melanoidins (M_W >5 kDa) are extracted at 70% efficiency, while hydrophilic antioxidants like chlorogenic acid degrade by 40% due to solvent-polarity mismatches (Gao et al., 2024). Recent advances in aqueous enzymatic extraction leverage protease (Alcalase® 2.4 L FG, 0.5% w/w) to hydrolyze oleosin-proteins at pH 7.5/50℃, liberating MRPs-protein conjugates (e.g., lysine-glucose adducts ↑25%) that enhance oxidative stability (induction period ↑3 h at 110℃) (Han et al., 2023). Meanwhile, supercritical CO_2 (SC-CO_2) extraction (40 MPa/60℃) selectively enriches tocopherols (90% recovery) but excludes polar MRPs (5-HMF <5 μg/g), necessitating post-extraction glycation induction via controlled heating (140℃/15 min) to regenerate flavor-active pyrazines (Lu et al., 2025). A comparative study on peanut oil revealed SC-CO_2-extracted oils required 30% longer roasting to match solvent-extracted oil flavor profiles, highlighting trade-offs between purity and sensory complexity (Figure 7). Roasting at a temperature of 160℃ improves the efficiency of solvent extraction by 15 to 18% in comparison to unroasted seeds. Additionally, infrared pretreatment at 140℃ results in a 12% increase in oil yield, while simultaneously preserving 20% more tocopherols and exhibiting 15% less degradation of pyrazines when compared to microwave-assisted treatment.

4.2 Mitigation Innovations: Precision vs. Practicality.

The mitigation of AA and HAA in thermally processed oilseeds represents a critical nexus between precision-driven technological advancements and pragmatic industrial implementation (Huang et al., 2025). As regulatory frameworks tighten and consumer demand for "clean label" products intensifies (Polachini et al., 2023), the food processing sector faces dual challenges: achieving quantifiable reductions in process contaminants while maintaining economic viability and sensory quality (F. Zhang et al., 2025). This section evaluates four emerging strategies—infrared-assisted dynamic roasting, antioxidant-mediated pathway interception, AI-driven predictive modeling, and scalable regulatory-practical frameworks—through the lens of their precision in targeting reaction pathways versus their adaptability to industrial constraints.

4.2.1 Infrared-Assisted Dynamic Roasting

Infrared-assisted dynamic roasting (IRDR) exemplifies a precision thermal intervention that minimizes collateral damage to heat-sensitive nutrients. By utilizing pulsed infrared heating at 140°C for 15 min (3–5 μm wavelength), this method achieves localized thermal penetration limited to <2 mm depth, thereby reducing bulk heating effects that drive widespread MR (Y. Yang et al., 2020). The selective energy absorption of AA at 210 nm allows real-time optical feedback control, maintaining process stability with a root mean square error (RMSE) of <5 μg/kg (H. Xu et al., 2024). This spatially confined heating reduces AA by 70% while preserving 85% of γ-tocopherols, a critical antioxidant in oilseeds often degraded by conventional roasting (Q. Xie et al., 2023). However, the technique's reliance on thin-layer configurations (<2 mm bed depth) complicates its integration into continuous industrial lines designed for bulk processing. Pilot studies indicate that scaling IRDR to commercial throughputs (>1 ton/hr) necessitates reengineering conveyor systems to ensure uniform exposure, potentially increasing energy costs by 18–22%. Despite these challenges, IRDR's ability to decouple thermal input from temporal duration offers a template for precision mitigation in low-moisture systems.

4.2.2 Antioxidant-Mediated Pathway Interception

The strategic deployment of natural antioxidants to intercept AA and HAA formation pathways highlights the synergy between molecular precision and formulation practicality (Ke & Li, 2023). Rosemary extract (0.1% w/w, carnosic acid $>40\%$) demonstrates dual functionality: it competitively scavenges lipid radicals (IC_{50} = 12 μM) to inhibit quinonimine-HAA adduct formation while paradoxically stabilizing pyrazine precursors, thereby preserving desirable Maillard flavors (Gadallah et al., 2024). This counterintuitive effect arises from carnosic acid's redox buffering capacity, which moderates radical chain reactions without fully suppressing Strecker degradation. Synergistic combinations with α-tocopherol (0.05% w/w) amplify this effect, achieving 78% suppression of PhIP while maintaining sensory profiles. Nevertheless, antioxidant efficacy is highly matrix-dependent; in oilseed matrices with high phospholipid content ($>2\%$), the hydrophobic partitioning of rosemary compounds reduces their bioavailability, necessitating emulsification or nanoencapsulation. Furthermore, regulatory limits on additive concentrations (e.g., EU Regulation 1129/2011 caps rosemary extracts at 0.3% w/w) constrain dosing flexibility, requiring formulation engineers to balance mitigation efficacy with compliance (*Commission Regulation (EU) No 1129/2011, 2011*).

4.2.3 AI-Driven Predictive Modeling

AI has emerged as a transformative tool for reconciling the stochastic nature of thermal processing with the demand for consistent AA mitigation (Bidyalakshmi et al., 2024). Gradient-boosted decision tree (GBDT) algorithms trained on 15,000 industrial batches identify six critical variables governing AA thresholds (K. Jiang et al., 2022; Schouten et al., 2022):

- Sugar-asparagine molar ratio ($\lambda = 0.87$),
- Initial water activity (aw = 0.4–0.6),
- Surface-to-volume heat flux (Φ >2.5 kW/m²),
- Chloride speciation (free vs. bound),
- Antioxidant redox potential (Eh <−150 mV),
- Real-time browning index (ΔE >8).

These models achieve predictive accuracy (R^2 >0.9) by dynamically weighting variables during roasting—for instance, prioritizing heat flux control when aw exceeds 0.55 to prevent localized caramelization. In pilot trials (n=120), AI implementation reduced AA variance by 92% through adaptive adjustments to belt speed (±5%) and IR emitter intensity (±15%). However, the "black box" nature of GBDT algorithms complicates regulatory acceptance, particularly in jurisdictions requiring explicit process validation. Additionally, the 25% capital cost increase for AI infrastructure remains a barrier for small-to-medium enterprises, though lifecycle analyses suggest a 40% reduction in post-processing detoxification expenses offsets this initial investment within 2–3 years.

4.2.4 Regulatory-Practical Balance

The ultimate translation of mitigation technologies into industry hinges on cost-benefit optimization aligned with regional regulatory landscapes. For example, microwave-assisted vacuum roasting (10 kPa, 130°C) demonstrates exceptional precision, achieving 90% AA/HAA reduction with <5% tocopherol loss, yet its energy consumption (35 kWh/ton) and unproven scalability limit adoption. Conversely, conventional hot-air roasting remains entrenched due to its low capital costs (0.5 M/linevs.2.1 M for AI-integrated systems), despite generating 2–3× higher AA levels. A hybrid approach combining IRDR’s precision with AI’s predictive power offers a middle path: preliminary data show that integrating optical feedback control into GBDT models reduces AA variance to <7 μg/kg while maintaining throughputs of 800 kg/hr (Figure 7). Critically, regulatory agencies increasingly recognize the need for risk-proportionate standards; the FDA's 2016 guidance on AA, for instance, emphasizes "as low as reasonably achievable" (ALARA) thrcesholds rather than fixed limits, encouraging innovation without mandating prohibitive technologies (Smit et al., 2025).

4.3 Process Optimization: Precision Glycation Engineering

Strategic modulation of Maillard pathways employs dual approaches to reconcile sensory enhancement with nutritional safety (Figure 7): Substrate Engineering:Xylose priming: Pre-treatment of flaxseeds with xylose (5% w/w) amplifies MRPs antioxidant capacity (FRAP: 43.65 μmol TE/g vs. 7.98 μmol TE/g in controls) through pyrrole carbaldehyde (PLP) formation, as confirmed by in silico quantum chemical modeling (HOMO-LUMO gap: 4.2 eV) (Y. Zhang et al., 2025). PLP's radical scavenging occurs at the pyrrole N-H group, with bond dissociation energies (BDE) of 78.3 kcal/mol, outperforming α-tocopherol (BDE: 82.1 kcal/mol). Phospholipid-sugar complexes: Phosphatidylethanolamine (PE)-xylose conjugates generated under microwave irradiation (800 W/2 min) exhibit interfacial stabilization in emulsions (zeta potential: -35 mV), delaying lipid oxidation (TBARS reduction: 60%) via synergistic antioxidant effects (Cao et al., 2022).

Environmental Control: Alkaline glycation: Lysine-glucose reactions at pH 10/110℃ proceed with a rate constant (k) of 0.12 min^{-1}, producing fluorescent MRPs (λex/em = 340/420 nm) that scavenge 80% of DPPH radicals at 0.8 mg/mL. This aligns with Pearson correlation analyses ($r = 0.94$, $p < 0.01$) linking fluorescence intensity to antioxidant capacity. Microbial β-glucosidase activation: Solid-state fermentation of soybeans with Aspergillus niger (72 h, 30℃) hydrolyzes cell wall-bound glucosides, elevating free glucose by 30% and subsequent MRPs yield (5-HMF ↑45%) upon roasting (S. Xu et al., 2024).

4.4 Analytical Convergence: AI-Driven MRPs Profiling

Emerging analytical frameworks are revolutionizing MR monitoring through multisensory data integration: Machine Learning (ML) Predictive Modeling: AA risk forecasting: Random forest algorithms trained on GC-MS datasets (n=1,200 samples) predict AA levels (R^2=0.93) using pyrazine/aldehyde ratios and Asn-glucose molar ratios (D. Cai et al., 2024). Feature importance analysis identifies 2,5-dimethylpyrazine as the primary predictor (Gini index=0.21).

Reaction pathway simulation: Graph neural networks (GNNs) map glycation pathways in peanut matrices, accurately predicting 5-HMF formation (RMSE=1.2 μg/g) under variable aw (0.3-0.7) and pH (4-9) conditions. Hyperspectral Imaging (HSI): Melanoidin quantification: Spectral indices at 580 nm (R^2=0.88 vs. HPLC) non-destructively track melanoidin accumulation in roasted sunflower seeds, enabling real-time process adjustments to limit browning (ΔE >15) (Fan et al., 2023). 3D Computer Vision: Maillard stage classification: Convolutional neural networks (CNNs) achieve 92% accuracy in classifying reaction stages using Lab* colorimetry and surface texture metrics (Ra=12-18 μm for intermediate-stage seeds vs. Ra=25-30 μm for terminal-stage) (He et al., 2024).

Challenges in Industrial Translation: In order to evaluate the feasibility of implementing AI and hyperspectral imaging within industrial settings, it is essential to consider factors such as cost, infrastructure, and regulatory requirements (Wan et al., 2025). Although these technologies facilitate real-time, non-destructive monitoring and optimization of processes, their adoption in industrial environments is frequently hindered by substantial capital expenditures (for instance, hyperspectral imaging systems can surpass $50,000) and the necessity for specialized personnel. Additionally, adherence to food safety regulations, such as those established by the European Food Safety Authority (EFSA) and the Food and Drug Administration (FDA), mandates the establishment of validated standard operating procedures and traceability protocols. Nevertheless, practical applications of these technologies are beginning to emerge. For instance, AI-driven "lights-out" oilseed processing facilities, such as China National Cereals, Oils and Foodstuffs Corporation's automated soybean crushing plant, exemplify the potential for fully automated quality control with minimal human involvement, leading to decreased labor costs and improved consistency (Liu et al., 2022). Additionally, hyperspectral imaging has been effectively utilized to distinguish between mold-contaminated and uncontaminated rapeseeds with an accuracy exceeding 95%, facilitating early-stage screening of raw materials (Y.R. Zhao et al., 2016). In the post-processing phase, it has been employed to evaluate the uniformity of oilcake color, a critical quality attribute that influences market acceptance. Lifecycle assessments suggest that optimization driven by artificial intelligence (AI) has the potential to reduce energy and detoxification costs by up to 40%, thereby enabling the recovery of initial investments within a period of 2 to 3 years. Although these technologies promise improved precision in control, scalability challenges persist. The generalization of AI models is frequently hindered by the insufficient diversity in training datasets across different oilseed species (e.g., palm and rapeseed), which necessitates the use of transfer learning for adaptations. Moreover, the substantial costs associated with hyperspectral imaging cameras, ranging from \$50,000 to \$100,000, present significant barriers to adoption for smaller milling operations. Additionally, maintaining microbial safety during fermentation-assisted glycation processes requires rigorous sterility protocols to mitigate the risks of mycotoxin contamination. Regulatory challenges also remain, as AI algorithms employed in quality grading must be both explainable and validated in accordance with Good Automated Manufacturing Practice (GAMP) guidelines, particularly when such decisions impact batch release. Future research should prioritize the integration of multi-omics approaches, encompassing lipidomics, metabolomics, and proteomics, as well as the implementation of Industry 4.0 frameworks, such as digital twins for thermal process simulation, to enhance predictive and personalized processing of oilseeds (refer to Figure 7).

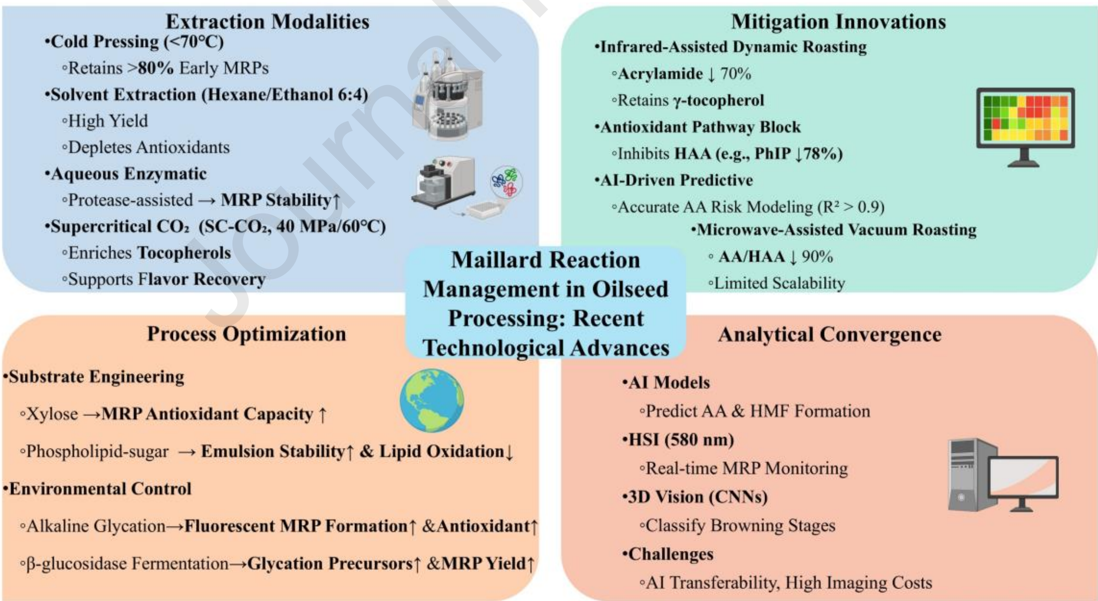


Figure 7 Recent Innovations in MRPs Control in Oilseed Processing

4.5 Limitations and Challenges of Smart Processing Technologies

Despite the potential benefits associated with advanced processing technologies—such as artificial intelligence-driven predictive modeling, hyperspectral imaging, and infrared-assisted roasting—their application in industrial contexts is hindered by several significant challenges. A primary constraint is scalability; although these technologies have shown efficacy in laboratory and pilot studies, their performance often declines when implemented on a larger scale. For example, infrared-assisted dynamic roasting (IRDR) and hyperspectral monitoring systems frequently face difficulties related to uneven heating and inconsistent spectral accuracy when operating beyond a throughput of 1 ton per hour, which necessitates substantial reengineering of mechanical conveyors and closed-loop control systems (Fakayode et al., 2025). Comparative analyses indicate that traditional drum roasting continues to surpass IRDR in terms of throughput reliability, despite its inferior precision in thermal management.

Furthermore, limitations associated with sensors impede broader adoption of these technologies. Optical and hyperspectral systems employed for real-time monitoring are particularly susceptible to variations in external environmental conditions, such as fluctuations in lighting, airborne particulates, and humidity, which are prevalent in oilseed processing facilities. These variables can distort spectral readings, necessitating frequent recalibration to uphold data integrity (Zheng et al., 2022). Additionally, delays in signal processing or inadequate calibration protocols may result in process drift and jeopardize product safety. Research comparing laboratory and in-line systems has demonstrated that even minor misalignments in sensor optics can diminish classification accuracy by more than 15% (Shaikh, 2024), underscoring the vulnerability of these technologies in industrial environments.

Cost considerations also present a significant barrier, particularly for small and medium-sized enterprises (SMEs). The implementation of smart systems entails not only initial capital expenditures (typically ranging from $50,000 to $100,000 for hyperspectral units) but also ongoing costs related to personnel training, software licensing, and regulatory compliance. Moreover, artificial intelligence models developed for specific oilseed varieties (e.g., rapeseed) often do not generalize effectively to other varieties (e.g., flaxseed or sunflower), necessitating transfer learning or retraining on species-specific datasets to achieve dependable predictive performance (Ma et al., 2024). To mitigate these challenges, future initiatives should prioritize the development of modular, cost-effective smart systems that incorporate inherent adaptability, while also advocating for industry-wide validation standards that reconcile precision, scalability, and regulatory compliance.

5. Conclusions and Future Perspectives

The thermal processing of oilseeds represents a complex balance between enhancing oxidative stability, flavor, and bioactivity while simultaneously posing risks related to nutrient degradation and process-induced contaminants. The MR plays a central role in this transformation, driving both desirable and undesirable changes. On one hand, thermal processing enhances oxidative stability, as evidenced by a 20–40% reduction in PV, and improves sensory attributes, with pyrazine concentrations increasing by 50–200 ppb. On the other hand, it poses significant safety concerns, including the formation of carcinogenic compounds such as AA at levels ranging from 50 to 450 μg/kg and the loss of essential nutrients, with lysine degradation reaching 30–50%. To address these challenges, several key advancements have emerged. First, mechanistic clarity in MR pathways, particularly in melanoidin polymerization within lipid-protein matrices, has facilitated improved control over reaction kinetics. Second, precision processing technologies, including AI-optimized thermal regimes (120–140℃, <30 min), have demonstrated potential in balancing the benefits of MRPs while mitigating associated risks. Finally, sustainable valorization strategies, such as enzymatic and microbial pre-treatments, have shown promise in redirecting reaction pathways to enhance nutritional quality while minimizing harmful byproduct formation. These advancements collectively provide a foundation for optimizing oilseed processing, ensuring both functional quality and food safety in industrial applications.

Future research endeavors should prioritize several critical areas to improve the precision, sustainability, and safety of oilseed processing. Firstly, the integration of multi-omics approaches, encompassing metabolomics, lipidomics, and proteomics, is vital for establishing connections between the formation of MRPs and their in vivo bioactivity, such as the kinetics of ACE inhibition. This understanding is crucial for elucidating the functional and health-related implications of these compounds. Secondly, the adoption of Industry 4.0 technologies is essential for the scalability of hyperspectral-AI systems, which facilitate real-time process control, thereby ensuring consistent product quality while reducing the formation of undesirable Maillard-derived compounds. Thirdly, the harmonization of regulatory standards is imperative to set uniform thresholds for AGEs and HAAs in edible oils, in accordance with the guidelines established by the EFSA and Codex Alimentarius, thereby enhancing consumer safety and regulatory compliance. Furthermore, the application of nanotechnology, particularly through nano-encapsulation techniques, holds significant promise for improving the bioavailability and stability of bioactive compounds generated during thermal processing. This approach may help mitigate nutrient loss while augmenting functional properties. Specifically, nano-encapsulation can safeguard thermally produced compounds, such as melanoidins, tocopherols, and antioxidant peptides derived from the MR, from oxidative degradation and gastrointestinal hydrolysis. For example, encapsulating melanoidin-rich fractions or lipid-soluble antioxidants, such as δ-tocopherol, within lipid-based nanocarriers (e.g., solid lipid nanoparticles or nanoemulsions) enhances their stability against variations in light, heat, and pH. Additionally, these delivery systems promote controlled release and improve intestinal absorption by increasing solubility and mucoadhesion, ultimately enhancing functional efficacy. Recent studies have also indicated that nano-encapsulated MR products exhibit extended radical-scavenging activity and enhanced cellular uptake in Caco-2 models, highlighting their potential as nutraceuticals.

To realize these advancements, interdisciplinary research that merges food science, materials science, and engineering will be crucial in developing next-generation processing technologies capable of precise thermal control and reduced nutrient degradation. Additionally, fostering international collaborations and establishing standardized protocols for evaluating the safety and quality of thermally processed oilseeds will facilitate global knowledge exchange and technological innovation in this domain. By harnessing these scientific and technological synergies, oilseed processing can evolve towards methodologies that are precision-driven, nutritionally optimized, and scalable, aligning with both regulatory standards and consumer expectations.

Credit author statement

Xinyu Li: Conceptualization, Methodology, Investigation, Software, Writing-original draft. Xinyue Liu: Conceptualization, Methodology, Investigation, Software, Writing-original draft. Zhiqiang Kong: Resources, Writing-review&editing, Data Curation. Lin Li: Resources, Writing-review&editing, Data Curation. Long Li: Resources, Visualization. Marie-Laure.Fauconnier: Conceptualization, Visualization, Project administration, Funding acquisition. Minmin Li: Conceptualization, Writing-review&editing, Visualization, Project

administration, Funding acquisition.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Acknowledgement

This study was supported by the Beijing Nova Program (20230484293) and the National Natural Science Foundation of China [grant number 32272443], the Youth Innovation of the Chinese Academy of Agricultural Sciences (Y2022QC12).

References

ALjahdali, N., & Carbonero, F. (2019). Impact of maillard reaction products on nutrition and health: Current knowledge and need to understand their fate in the human digestive system. Critical Reviews in Food Science and Nutrition, 59(3), 474–487. https://doi.org/10.1080/10408398.2017.1378865

Allay, A., Benkirane, C., Ben Moumen, A., Fauconnier, M.-L., Bouakline, H., Nkengurutse, J., Serghini Caid, H., Elamrani, A., & Mansouri, F. (2025). Optimizing ethanol-modified supercritical CO_2 extraction for enhanced bioactive compound recovery in hemp seed oil. Scientific Reports, 15(1), 8551. https://doi.org/10.1038/s41598-025-91441-x

Alsafra, Z., Kuuliala, L., Scholl, G., Saegerman, C., Eppe, G., & De Meulenaer, B. (2023). Characterizing the formation of process contaminants during coffee roasting by multivariate statistical analysis. Food Chemistry, 427, 136655. https://doi.org/10.1016/j.foodchem.2023.136655

Bachir, N., Haddarah, A., Sepulcre, F., & Pujola, M. (2022). Formation, mitigation, and detection of acrylamide in foods. Food Analytical Methods, 15(6), 1736–1747. https://doi.org/10.1007/s12161-022-02239-w

Bidyalakshmi, Thingujam., Jyoti, B., Mansuri, S. M., Srivastava, A., Mohapatra, D., Kalnar, Y. B., Narsaiah, K., & Indore, N. (2024). Application of artificial intelligence in food processing: Current status and future prospects. Food Engineering Reviews. https://doi.org/10.1007/s12393-024-09386-2

Bolchini, S., Nardin, T., Morozova, K., Scampicchio, M., & Larcher, R. (2025). Antioxidant maillard reaction products from milk whey: A food by-product valorisation. Foods (Basel, Switzerland), 14(3), 450. https://doi.org/10.3390/foods14030450

Bork, L. V., Baumann, M., Stobernack, T., Rohn, S., & Kanzler, C. (2023). Colorants and antioxidants deriving from methylglyoxal and heterocyclic maillard reaction intermediates. Antioxidants (Basel, Switzerland), 12(9), 1788. https://doi.org/10.3390/antiox12091788

Cai, D., Li, X., Liu, H., Wen, L., & Qu, D. (2024). Machine learning and flavoromics-based research strategies for determining the characteristic flavor of food: A review. Trends in Food Science & Technology, 154, 104794. https://doi.org/10.1016/j.tifs.2024.104794

Cai, Z., Jiang, Q., Zhang, R., Ma, Y., Chen, K., Zheng, S., Li, P., Zeng, C., & Zhang, H. (2025). Comparison of extraction and refinement techniques for volatile compound analysis in camellia oil. Food Chemistry, 469, 142501. https://doi.org/10.1016/j.foodchem.2024.142501

Cai, Z., Li, K., Lee, W. J., Reaney, M. T. J., Zhang, N., & Wang, Y. (2021). Recent progress in the thermal treatment of oilseeds and oil oxidative stability: A review. Fundamental Research, 1(6), 767–784. https://doi.org/10.1016/j.fmre.2021.06.022

Cao, J., Yan, H., & Liu, L. (2022). Optimized preparation and antioxidant activity of glucose-lysine maillard reaction products. LWT-Food Science and Technology, 161, 113343. https://doi.org/10.1016/j.lwt.2022.113343

Carré, P., Bothe, S., Borah, C. D., Piofczyk, T., & Hadjiali, S. (2025). Solvent solutions: Comparing extraction methods for edible oils and proteins in a changing regulatory landscape. Part 5: impacts on the oil quality. Ocl, 32, 6. https://doi.org/10.1051/ocl/2025001

Cha, C.-Y., & Lee, K.-G. (2020). Effect of roasting conditions on the formation and kinetics of furan in various nuts. Food Chemistry, 331, 127338. https://doi.org/10.1016/j.foodchem.2020.127338

Commission Regulation (EU) No 1129/2011. (2011). Official Journal of the European Union.

Du, W., Wang, Y., Ma, Q., Li, X., Bai, S., Cui, W., Fan, B., & Wang, F. (2024). Effect of 2-alkenals on the maillard reaction of cysteine-glucose: Initial stage intermediate formation and flavor compound generation pathways. LWT-Food Science and Technology, 192, 115741. https://doi.org/10.1016/j.lwt.2024.115741

Fakayode, O. A., Ojoawo, O. O., Zhou, M., Wahia, H., & Ogunlade, C. A. (2025). Revolutionizing food processing with infrared heating: New approaches to quality and efficiency. Food Physics, 2, 100046. https://doi.org/10.1016/j.foodp.2024.100046

Fan, M., Xu, X., Lang, W., Wang, W., Wang, X., Xin, A., Zhou, F., Ding, Z., Ye, X., & Zhu, B. (2023). Toxicity, formation, contamination, determination and mitigation of acrylamide in thermally processed plant-based foods and herbal medicines: A review. Ecotoxicology and Environmental Safety, 260, 115059. https://doi.org/10.1016/j.ecoenv.2023.115059

Gadallah, A. H., Hafez, R. S., Fahim, K. M., & Ahmed, L. I. (2024). Application of rosemary oil nano-emulsion as antimicrobial and antioxidant natural alternative in pasteurized cream and karish cheese. International Journal of Food Microbiology, 422, 110823. https://doi.org/10.1016/j.ijfoodmicro.2024.110823

Gao, P., Zhou, Z., Wang, S., Zheng, Y., Liu, C., Zhong, W., Yin, J., & Reaney, M. J. T. (2024). Solvent extraction of triadica sebifera seed oil: Yield, lipid composition, and antioxidant properties. LWT-Food Science and Technology, 208, 116715. https://doi.org/10.1016/j.lwt.2024.116715

Guo, Q., Xu, S., Liu, H.-M., Liu, M.-W., Wang, C.-X., Qin, Z., & Wang, X.-D. (2022). Effects of roasting temperature and duration on color and flavor of a sesame oligosaccharide-protein complex in a maillard reaction model. Food Chemistry: X, 16, 100483. https://doi.org/10.1016/j.fochx.2022.100483

He, Q., Huang, H., & Wang, Y. (2024). Detection technologies, and machine learning in food: Recent advances and future trends. Food Bioscience, 62, 105558. https://doi.org/10.1016/j.fbio.2024.105558

Hidalgo, F. J., & Zamora, R. (2023). Carbonyl-trapping by phenolics and the inhibition of the formation of carcinogenic heterocyclic aromatic amines with the structure of aminoimidazoazaarene in beef patties. Food Chemistry, 425, 136505. https://doi.org/10.1016/j.foodchem.2023.136505

Hu, H., Liu, X., Jiang, L., Zhang, Q., & Zhang, H. (2021). The relationship between acrylamide and various components during coffee roasting and effect of amino acids on acrylamide formation. Journal of Food Processing and Preservation, 45(5). https://doi.org/10.1111/jfpp.15421

Huang, Y., Li, H., Yu, X., Zhang, F., Wang, A., Wan, X., Zhuang, P., Jiao, J., & Zhang, Y. (2025). Foodomics-based chemical profiling and signature compound characterization of air-fried potato chips: The effect of thermal processing and fish oil treatment on advancing safety, nutrition, and flavor attributes. Food Bioscience, 66, 106211. https://doi.org/10.1016/j.fbio.2025.106211

Huang, Y., Liu, C., Ge, Z., Huang, F., Tang, H., Zhou, Q., Liu, R., Huang, J., & Zheng, C. (2023). Influence of different thermal treatment methods on the processing qualities of sesame seeds and cold-pressed oil. Food Chemistry, 404, 134683. https://doi.org/10.1016/j.foodchem.2022.134683

Ji, J., Zhang, Y., Wang, D., Wang, Y., & Hou, J. (2023). Impact of seed-roasting treatment on polycyclic aromatic hydrocarbons, 3-MCPD esters, heterocyclic amines and volatile components formation in sunflower oil. LWT-Food Science and Technology, 185, 115121. https://doi.org/10.1016/j.lwt.2023.115121

Jia, W., Guo, A., Zhang, R., & Shi, L. (2023). Mechanism of natural antioxidants regulating advanced glycosylation end products of maillard reaction. Food Chemistry, 404, 134541. https://doi.org/10.1016/j.foodchem.2022.134541

Jiang, K., Huang, C., Liu, F., Zheng, J., Ou, J., Zhao, D., & Ou, S. (2022). Origin and fate of acrolein in foods. Foods, 11(13), 1976. https://doi.org/10.3390/foods11131976

Jiang, L., Zheng, K., Hou, X., & Darwish, I. A. (2025). Maillard-induced chia seed mucilage glycation-modified whey protein isolate conjugate: Insights from functional properties and untargeted metabolomics. Food Bioscience, 63, 105692. https://doi.org/10.1016/j.fbio.2024.105692

Kang, M. J., & Suh, J. H. (2022). Metabolomics as a tool to evaluate nut quality and safety. Trends in Food Science & Technology, 129, 528–543. https://doi.org/10.1016/j.tifs.2022.11.002

Ke, C., & Li, L. (2023). Influence mechanism of polysaccharides induced maillard reaction on plant proteins structure and functional properties: A review. Carbohydrate Polymers, 302, 120430. https://doi.org/10.1016/j.carbpol.2022.120430

Li, X., Zhang, L., Zhang, Y., Wang, D., Wang, X., Yu, L., Zhang, W., & Li, P. (2020). Review of NIR spectroscopy methods for nondestructive quality analysis of oilseeds and edible oils. Trends in Food Science & Technology, 101, 172–181. https://doi.org/10.1016/j.tifs.2020.05.002

Lin, Z., & Grasso, S. (2025). Exploring seed-based upcycled oils: Types, extraction processes, and emerging applications. Critical Reviews in Food Science and Nutrition, 1–20. https://doi.org/10.1080/10408398.2025.2472895

Liu, F., Wang, F., Wang, X., Liao, G., Zhang, Z., Yang, Y., & Jiao, Y. (2022). Rapeseed variety recognition based on hyperspectral feature fusion. Agronomy, 12(10), Article 10. https://doi.org/10.3390/agronomy12102350

Lu, W.-C., Chiu, C.-S., Chan, Y.-J., Mulio, A. T., & Li, P.-H. (2025). New perspectives on different sacha inchi seed oil extractions and its applications in the food and cosmetic industries. Critical Reviews in Food Science and Nutrition, 65(3), 475–493. https://doi.org/10.1080/10408398.2023.2276882

Ma, Y., Chen, S., Ermon, S., & Lobell, D. B. (2024). Transfer learning in environmental remote sensing. Remote Sensing of Environment, 301, 113924. https://doi.org/10.1016/j.rse.2023.113924

Nie, C., Li, Y., Qian, H., Ying, H., & Wang, L. (2022). Advanced glycation end products in food and their effects on intestinal tract. Critical Reviews in Food Science and Nutrition, 62(11), 3103–3115. https://doi.org/10.1080/10408398.2020.1863904

Nomi, Y., Anazawa, T., Shinzawa, K., Tamura, M., & Matsumoto, H. (2025). Identification of lactose-derived α-dicarbonyl compounds in dairy products and elucidation of their formation mechanism. Journal of Agricultural and Food Chemistry, 73(1), 781–789. https://doi.org/10.1021/acs.jafc.4c08966

Polachini, T. C., Norwood, E.-A., Le-Bail, P., & Le-Bail, A. (2023). Clean-label techno-functional ingredients for baking products – a review. Critical Reviews in Food Science and Nutrition, 63(25), 7461–7476. https://doi.org/10.1080/10408398.2022.2046541

Pucci, M., Akıllıoğlu, H. G., Bevilacqua, M., Abate, G., & Lund, M. N. (2024). Investigation of maillard reaction products in plant-based milk alternatives. Food Research International (Ottawa, Ont.), 198, 115418. https://doi.org/10.1016/j.foodres.2024.115418

Qiu, C., Meng, Y., Zhang, Z., Li, X., McClements, D. J., Li, G., Jiang, L., Wen, J., Jin, Z., & Ji, H. (2025). Enhancement of soy protein functionality by conjugation or complexation with polysaccharides or polyphenols: A review. Comprehensive Reviews in Food Science and Food Safety, 24(1), e70095. https://doi.org/10.1111/1541-4337.70095

Rufián-Henares, J. A., & Morales, F. J. (2007). Functional properties of melanoidins: In vitro antioxidant, antimicrobial and antihypertensive activities. Food Research International, 40(8), 995–1002. https://doi.org/10.1016/j.foodres.2007.05.002

Schouten, M. A., Tappi, S., Glicerina, V., Rocculi, P., Angeloni, S., Cortese, M., Caprioli, G., Vittori, S., & Romani, S. (2022). Formation of acrylamide in biscuits during baking under different heat transfer conditions. LWT-Food Science and Technology, 153, 112541. https://doi.org/10.1016/j.lwt.2021.112541

Shaikh, M. S. (2024). Hyperspectral imaging for in-situ applications: Methods to improve the classification of materials using hyperspectral imaging. Mid Sweden University.

Shi, B., Guo, X., Liu, H., Jiang, K., Liu, L., Yan, N., Farag, M. A., & Liu, L. (2024). Dissecting maillard reaction production in fried foods: Formation mechanisms, sensory characteristic attribution, control strategy, and gut homeostasis regulation. Food Chemistry, 438, 137994. https://doi.org/10.1016/j.foodchem.2023.137994

Smit, I., Vosmann, K., Weber, L., Truberg, B., Muders, K., Bülbül, M. K., Demirel, U., Çalışkan, M. E., & Haase, N. U. (2025). Potential of near-infrared spectroscopy (NIRS) for prediction of acrylamide formation in french fries in the potato breeding process. Food Chemistry, 463, 141214. https://doi.org/10.1016/j.foodchem.2024.141214

Sun, A., Wu, W., Soladoye, O. P., Aluko, R. E., Bak, K. H., Fu, Y., & Zhang, Y. (2022). Maillard reaction of food-derived peptides as a potential route to generate meat flavor compounds: A review. Food Research International, 151, 110823. https://doi.org/10.1016/j.foodres.2021.110823

Twarda-Clapa, A., Olczak, A., Białkowska, A. M., & Koziołkiewicz, M. (2022). Advanced glycation end-products (AGEs): Formation, chemistry, classification, receptors, and diseases related to AGEs. Cells, 11(8), 1312. https://doi.org/10.3390/cells11081312

Valle-Sánchez, S. L., Rodríguez-Ramírez, R., Ávila-Villa, L. A., Villa-Lerma, A. G., Wall-Medrano, A., De La Rosa, L. A., Muñoz-Bernal, Ó. A., González-Córdova, A. F., & Arellano-Gil, M. (2025). Phenolic compounds profile in extracts of smilax spp., antioxidant activity, and inhibition of advanced glycation end products. Food Chemistry, 463, 141389. https://doi.org/10.1016/j.foodchem.2024.141389

Wan, G., He, J., Meng, X., Liu, G., Zhang, J., Ma, F., Zhang, Q., & Wu, D. (2025). Hyperspectral imaging technology for nondestructive identification of quality deterioration in fruits and vegetables: A review. Critical Reviews in Food Science and Nutrition, 1–30. https://doi.org/10.1080/10408398.2025.2487134

Wang, R., Zhai, X., Hartel, R. W., Chang, Y., Pang, W., Han, W., Lv, H., & Wang, S. (2024). Effects of saccharide type and extended heating on the maillard reaction and physicochemical properties of high-solid gelatin gels. Food Chemistry, 459, 140249. https://doi.org/10.1016/j.foodchem.2024.140249

Wei, P., Guo, J., Lian, J., & Wang, C. (2025). Combination manner of sampling method and model structure: The key factor for rice mapping based on sentinel-1 images using data-driven machine learning. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 99, 1–20. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing. https://doi.org/10.1109/JSTARS.2025.3550109

Xie, Q., Wang, C., Peng, L., Dong, Y., Gao, Y., Xu, J., Ping, H., & Liu, S. (2023). Effect of vacuum roasting on total selenium content of selenium-enriched rapeseed, maillard reaction products, oxidative stability and physicochemical properties of selenium-enriched rapeseed oil. Foods, 12(17), 3240.

Xie, X., Wang, Y., Wen, B., Tian, J., Cheng, Z., Tang, S., Nie, Y., Wu, X., Guo, X., & Li, B. (2025). Characterization and metabolism pathway of volatile compounds in blueberries of different varieties and origins analyzed via HS-GC-IMS and HS-SPME-GC–MS. Food Chemistry, 143813. https://doi.org/10.1016/j.foodchem.2025.143813

Xu, H., Liu, H., Yin, W., Xiong, X., & Xu, X. (2024). Roasted sesame oil: A review on production technology, flavor chemistry, and other related issues. Journal of the American Oil Chemists' Society, 2024, 12917. https://doi.org/10.1002/aocs.12917

Xu, S., Zhou, H., Xu, B., Liu, W., Hu, W., Xu, Q., Hong, J., Liu, Y., & Li, X. (2024). Deciphering layer formation in red heart qu: A comprehensive study of metabolite profile and microbial community influenced by raw materials and environmental factors. Food Chemistry, 451, 139377. https://doi.org/10.1016/j.foodchem.2024.139377

Yang, D., Chen, C., Zhao, D., & Li, C. (2025). Impact of ultra-processed meat products on human health: Review and outlook. Journal of Food Science, 90(2), e70040. https://doi.org/10.1111/1750-3841.70040

Yang, H., Li, W., Lu, B., Zi, L., Xu, N., & Guo, L. (2024). Effect of different hot air drying process on flavor compounds and maillard reaction products of boletus edulis by HS-SPME/GC-MS coupled with multivariate analysis. LWT-Food Science and Technology, 198, 116055. https://doi.org/10.1016/j.lwt.2024.116055

Yang, J., Wen, C., Duan, Y., Deng, Q., Peng, D., Zhang, H., & Ma, H. (2021). The composition, extraction, analysis, bioactivities, bioavailability and applications in food system of flaxseed (linum usitatissimum L.) oil: A review. Trends in Food Science & Technology, 118, 252–260. https://doi.org/10.1016/j.tifs.2021.09.025

Yang, Y., Zhang, M., Hua, J., Deng, Y., Jiang, Y., Li, J., Wang, J., Yuan, H., & Dong, C. (2020).

Quantitation of pyrazines in roasted green tea by infrared-assisted extraction coupled to headspace solid-phase microextraction in combination with GC-QqQ-MS/MS. Food Research International, 134, 109167. https://doi.org/10.1016/j.foodres.2020.109167

Yıldız, K., Özdikicierler, O., & Günç Ergönül, P. (2024). The trend in mitigation strategies of 3-monochloropropane-1,2-diol and glycidyl esters in edible vegetable oils: Today and tomorrow. Food Technology and Biotechnology, 62(3), 326–345. https://doi.org/10.17113/ftb.62.03.24.8260

Zhang, F., Yu, X., Tian, Y., Zeng, J., Zhuang, P., Jia, W., & Zhang, Y. (2025). Joint control of multiple food processing contaminants in maillard reaction: A comprehensive review of health risks and prevention. Comprehensive Reviews in Food Science and Food Safety, 24(2), e70138. https://doi.org/10.1111/1541-4337.70138

Zhang, W., Cao, X., & Liu, S. Q. (2020). Aroma modulation of vegetable oils-a review. Critical Reviews in Food Science and Nutrition, 60(9), 1538–1551. https://doi.org/10.1080/10408398.2019.1579703

Zhang, Y., Li, K., Du, Y., Wang, L., Xiong, Q., Zhang, N., Yue, X., Chen, J., Reaney, M. J. T., Wang, Y., & Cai, Z. (2025). Maillard reaction products derived from xylose-phosphatidylethanolamine: Potential anti-oxidative substances from hot-pressed flaxseed oil. Food Chemistry, 476, 143429. https://doi.org/10.1016/j.foodchem.2025.143429

Zhang, Y., Li, X., Lu, X., Sun, H., & Wang, F. (2021). Effect of oilseed roasting on the quality, flavor and safety of oil: A comprehensive review. Food Research International, 150, 110791. https://doi.org/10.1016/j.foodres.2021.110791

Zhao, P., Zheng, D., Li, T., Peng, H., He, J., Shi, J., Zhao, J., Li, P., & Zhang, W. (2025). Maillard reaction based chitosan-monosaccharide films and the application in fruit preservation. Food Hydrocolloids, 166, 111269. https://doi.org/10.1016/j.foodhyd.2025.111269

Zhao, Y.-R., Yu, K.-Q., Li, X., & He, Y. (2016). Detection of fungus infection on petals of rapeseed (brassica napus L.) using NIR hyperspectral imaging. Scientific Reports, 6(1), 38878. https://doi.org/10.1038/srep38878

Zheng, L., Zhao, M., Zhu, J., Huang, L., Zhao, J., Liang, D., & Zhang, D. (2022). Fusion of hyperspectral imaging (HSI) and RGB for identification of soybean kernel damages using ShuffleNet with convolutional optimization and cross stage partial architecture. Frontiers in Plant Science, 13, 1098864. https://doi.org/10.3389/fpls.2022.1098864

Zou, R., Xu, J., Guo, Z., Wang, Z., Huang, Z., Wang, L., & Jiang, L. (2025). Exploring sustainable sources and modification techniques of plant-based alternative proteins for high internal phase emulsion systems: From camellia oleifera seed meal, copra meal, and soybean meal. Food Hydrocolloids, 166, 111256. https://doi.org/10.1016/j.foodhyd.2025.111256

Highlights

- Precision thermal control minimizes harmful Maillard reaction byproducts in oilseeds.
- AI-driven monitoring optimizes Maillard reaction pathways for food safety.
- Smart processing balances bioactive retention and contaminant reduction.