

Effects of Food Processing on Nutrient Bioavailability and Metabolic Health

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ABSTRACT

Background and Objective: The global rise in food processing technologies has revolutionized food availability and safety but has introduced complex implications for nutrient bioavailability and metabolic health. While some processing methods enhance nutrient release and absorption, others degrade essential compounds or create harmful byproducts, contributing to chronic disease risk. This review integrates biochemical, nutritional, and epidemiological perspectives to elucidate how different processing techniques influence nutrient dynamics and health outcomes.

Materials and Methods: A systematic literature review was conducted across PubMed, ScienceDirect, Scopus, and Web of Science, covering studies from 2010 to 2025. Selection criteria emphasized experimental or observational designs evaluating food processing methods and their impacts on nutrient bioavailability and metabolic parameters. Data were synthesized based on processing intensity (minimal, moderate, ultra-processed), nutrient type, and health outcome, following PRISMA guidelines. **Results:** Thermal and ultra-processing methods frequently degrade heat-sensitive vitamins, oxidize lipids, denature proteins, and impair mineral absorption through antinutrient interactions. They also promote glycemic dysregulation, gut microbiota imbalance, and pro-inflammatory states, exacerbating risks for obesity, diabetes, and cardiovascular disease. Conversely, non-thermal and moderate techniques (e.g., fermentation, high-pressure processing) preserve nutrient integrity and improve digestibility, while enhancing microbiome-supportive functions. Processing impacts vary by nutrient type, food matrix, and method used. **Conclusion:** Food processing exerts profound effects on nutrient bioavailability and metabolic regulation. Strategies such as adopting non-thermal technologies and targeted fortification are critical for mitigating adverse effects. A balanced, evidence-informed approach is essential to align food processing with public health objectives and nutritional adequacy.

KEYWORDS

Nutrient bioavailability, food processing, metabolic health, ultra-processed foods, gut microbiota, non-thermal technologies, micronutrient degradation, glycemic response, dietary policy

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INTRODUCTION

Over the past century, the global food landscape has been transformed by a wide array of food processing technologies. These methods have evolved to address challenges related to food preservation, safety, shelf life, taste, and accessibility¹. While food processing has contributed substantially to improving food security and reducing foodborne illnesses, it has simultaneously emerged as a double-edged sword, particularly in the context of nutrient bioavailability and metabolic health^{1,2}.

Food processing encompasses a continuum from minimal alterations, such as washing, freezing, and drying, to more intensive interventions like pasteurization, hydrogenation, extrusion, fermentation, and fortification². Modern industrial food processing, particularly the ultra-processing of foods, frequently involves mechanical, chemical, and thermal steps that substantially modify the food matrix. These alterations not only influence taste, appearance, and palatability but also profoundly affect the chemical structure and physiological accessibility of nutrients^{2,3}.

Nutrient bioavailability is defined as the proportion of a nutrient that is released from its matrix in the gastrointestinal tract, absorbed, and utilized for normal physiological functions. This concept is critical to understanding how processing impacts nutritional status and metabolic function. While certain processing methods enhance bioavailability for example, thermal treatment can inactivate anti-nutritional factors or soften plant cell walls others may degrade heat-labile nutrients, cause nutrient leaching, or generate compounds that interfere with absorption³.

From a biochemical perspective, processing influences not only macronutrients such as carbohydrates, proteins, and lipids but also micronutrients including vitamins, minerals, and phytochemicals. For instance, gelatinization of starch increases its digestibility and glycemic index, while Maillard reactions during high-temperature cooking result in the formation of Advanced Glycation End Products (AGEs), which have been implicated in oxidative stress and chronic disease development^{3,4}.

The increasing prevalence of Ultra-Processed Foods (UPFs) in contemporary diets has raised major public health concerns. UPFs typically contain added sugars, refined starches, hydrogenated fats, emulsifiers, and synthetic additives, but are often depleted in fiber, essential fatty acids, and micronutrients³. Epidemiological evidence consistently links higher consumption of UPFs with an increased risk of metabolic syndrome, type 2 diabetes, cardiovascular disease, obesity, and non-alcoholic fatty liver disease⁴.

Beyond their direct nutritional implications, food processing also affects gut microbiota composition and function, which serves as a mediator of metabolic health. The reduction in fermentable fiber and the increase in food additives in processed foods can disturb microbial diversity and promote inflammation⁴.

Given these complexities, a nuanced understanding of how specific processing methods influence the biochemical properties, bioavailability, and physiological effects of nutrients is essential. This review seeks to provide a comprehensive examination of the scientific mechanisms through which food processing impacts nutrient utilization and metabolic health. By integrating evidence from nutritional biochemistry, food technology, and epidemiology, this work aims to inform both public health policy and food industry practices.

MATERIALS AND METHODS

Literature search strategy: A structured and comprehensive literature search was conducted using electronic databases including PubMed, ScienceDirect, Scopus, and Web of Science to gather peer-reviewed publications from 2010 to 2025⁵. The search focused on studies examining the impact of

food processing on nutrient bioavailability and metabolic health. Keywords used in various combinations included: "Food processing", "nutrient bioavailability", "micronutrient degradation", "metabolic disorders", "thermal processing", "non-thermal technologies", "gut microbiota", and "ultra-processed foods"⁵. The inclusion criteria comprised:

- Peer-reviewed journal articles published between 2010 and 2025
- Human or *in vitro/in vivo* studies with a clear experimental or observational design
- Studies assessing either food processing techniques or metabolic health outcomes
- Exclusion criteria included non-English articles, opinion pieces, and those without full-text availability^{5,6}

Study selection and data extraction: Titles and abstracts of all retrieved articles were screened independently by two reviewers. Full-text screening was conducted for potentially eligible articles. Discrepancies were resolved through consensus or consultation with a third reviewer. Extracted data included:

- Study type (e.g., randomized controlled trial, cohort study, and *in vitro/in vivo* experimental design)
- Food processing method studied
- Type of nutrients affected
- Bioavailability assessment method
- Metabolic health outcomes measured
- Statistical tools used
- A PRISMA-based flow diagram was developed to track the selection process⁶

This PRISMA-based flowchart (Fig. 1) provides a visual summary of the rigorous screening and selection protocol adopted in this review. It complements the narrative in Section 2.2 by depicting each critical stage of the literature search and inclusion process. The transparent identification, screening, and inclusion of high-quality studies align with best practices for evidence synthesis in nutrition science⁶. The diagram ensures traceability and reproducibility, which are essential for evaluating dietary patterns, nutrient transformations, and processing effects on nutrient bioavailability^{6,7}.

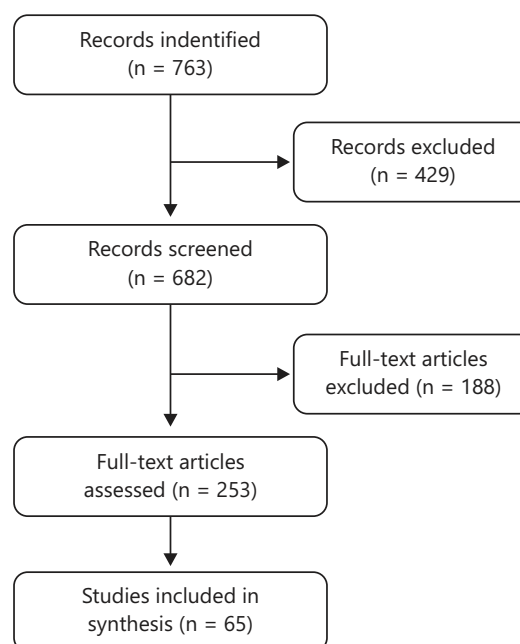


Fig 1: Flowchart of literature search and study selection process^{6,7}

Figure 1 illustrates the systematic selection of studies included in this review, adapted from the PRISMA 2020 guidelines. A total of 763 records were initially identified from databases. After the removal of duplicates and irrelevant entries, 682 studies were screened by title and abstract, resulting in 253 full-text articles assessed for eligibility. Of these, 188 articles were excluded due to reasons such as lack of nutritional outcome data or irrelevance to food processing methods. Ultimately, 65 peer-reviewed studies were included in the final synthesis. This structured approach ensured the inclusion of studies with robust methodologies addressing the impact of food processing on nutrient bioavailability and metabolic health^{6,7}.

Classification of processing techniques: Food processing techniques were categorized according to the NOVA classification system⁷, and grouped as:

- Minimal processing: e.g., drying, washing, freezing
- Moderate processing: e.g., fermentation, pasteurization, milling
- Ultra-processing: e.g., extrusion, hydrogenation, artificial additive incorporation
- This classification facilitated comparison of effects across different processing intensities⁷

Nutrient bioavailability assessment: Nutrient bioavailability data were interpreted from original articles using the following analytical methods:

- *In vitro* digestion models, simulating gastrointestinal conditions to evaluate nutrient release and absorption potential⁸
- Caco-2 cell assays, used to simulate intestinal absorption of micronutrients⁵
- *In vivo* studies, using animal or human models to assess plasma concentrations or metabolic endpoints⁸
- Stable isotope labeling, particularly for iron, calcium, and vitamin D bioavailability^{8,9}

Metabolic health assessment: Studies reporting direct impacts of food processing on metabolic health parameters were included if they measured:

- Blood glucose, insulin sensitivity/resistance
- Lipid profiles (HDL, LDL, triglycerides)
- Inflammatory biomarkers (CRP, IL-6, TNF-alpha)
- Gut microbiota composition via 16S rRNA sequencing
- Body composition (BMI, visceral adiposity)
- Longitudinal outcomes for obesity, T2DM, and CVD
- Analytical methods included ELISA, chromatography, mass spectrometry, and metagenomic analysis, depending on the study⁹

Data synthesis: Findings were synthesized qualitatively based on nutrient type and processing method. Where possible, effect sizes and risk ratios from cohort and case-control studies were tabulated. Biochemical mechanisms (e.g., lipid oxidation, AGE formation, and vitamin degradation) were compared across techniques. Trends from randomized controlled trials and systematic reviews were highlighted to contextualize epidemiological evidence¹⁰.

RESULTS AND DISCUSSION

This chapter synthesizes contemporary findings from biochemical, nutritional, and epidemiological studies, integrating how various food processing methods impact nutrient bioavailability and, consequently, metabolic health outcomes. The discussion is structured around nutrient categories: carbohydrates, lipids, proteins, and micronutrients, followed by insights into emerging processing technologies and public health implications.

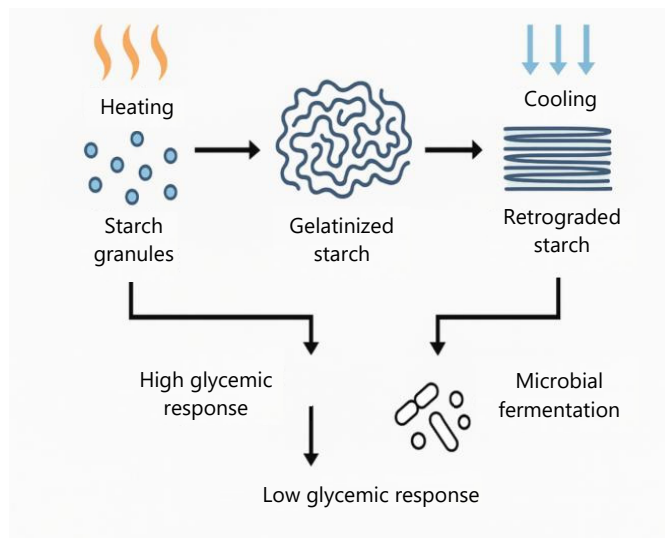


Fig. 2: Transformation of starch during gelatinization and retrogradation and its impact on glycemic response and microbial fermentation¹¹⁻¹³

Effects of processing on carbohydrate bioavailability and glycemic response: Processing methods significantly influence carbohydrate structure, digestibility, and glycemic potential. Thermal processing promotes starch gelatinization, increasing enzymatic accessibility and glycemic index¹¹. Conversely, retrogradation during cooling can form resistant starch, beneficial for glycemic control and gut fermentation¹¹.

This diagram illustrates the physicochemical transformation of starch during processing and its metabolic consequences. When starch granules are heated in the presence of water, gelatinization occurs, disrupting crystalline structures and making starch more accessible to digestive enzymes, thereby raising glycemic response. Upon subsequent cooling, retrogradation leads to the reformation of ordered, less digestible structures known as resistant starch, which lowers glycemic impact and serves as a fermentable substrate for beneficial gut bacteria. These transitions influence postprandial blood glucose levels and support the generation of Short-Chain Fatty Acids (SCFAs), with implications for inflammation modulation and gut health¹¹⁻¹³.

Figure 2 deepens the explanation by visually capturing the transformation of starch during heating and cooling. Gelatinized starch produced during cooking is enzymatically digestible, contributing to a higher glycemic index. In contrast, when this starch undergoes retrogradation upon cooling, it resists digestion, becomes metabolized by gut microbiota, and reduces glycemic load while enhancing colonic health through SCFA production^{11,12}. These biochemical changes highlight the importance of food structure in modulating glucose metabolism and inflammatory pathways¹².

Furthermore, excessive refining eliminates dietary fiber, altering glucose-insulin homeostasis. Fiber-deficient diets are associated with dysbiosis and metabolic endotoxemia, contributing to insulin resistance^{12,13}. High-temperature baking and frying may also produce Maillard reaction products like Advanced Glycation End Products (AGEs), which are linked to oxidative stress and impaired glucose metabolism¹³.

Lipid transformation, oxidation, and cardiometabolic risk: Fat processing, including frying, hydrogenation, and emulsification, modifies lipid structures. High-temperature frying initiates lipid peroxidation, producing toxic aldehydes and reactive oxygen species¹⁴. These compounds can induce endothelial dysfunction and accelerate atherosclerosis¹⁴.

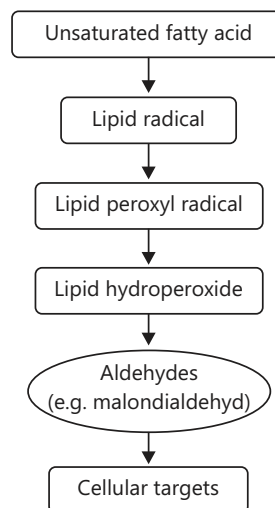


Fig. 3: Lipid peroxidation pathway: From unsaturated fatty acids to aldehyde formation and cellular impact¹⁴⁻¹⁶

Partially hydrogenated oils create trans fatty acids (TFAs), known to increase LDL and decrease HDL cholesterol^{14,15}. This dyslipidemia profile is a well-established risk factor for cardiovascular disease. Regulatory bans on TFAs have reduced related disease burdens globally¹⁵.

Figure 3 visually supports by illustrating how thermal processing, particularly frying or grilling in oxygen-rich environments, catalyzes lipid peroxidation in food systems. The production of reactive aldehydes such as malondialdehyde highlights a critical pathway through which oxidized lipids contribute to chronic inflammation and metabolic disease risk. These byproducts interfere with mitochondrial function, activate inflammatory cascades, and exacerbate cardiovascular pathologies when consumed regularly^{15,16}. This biochemical cascade underscores the necessity of monitoring oxidative stability in processed fats and minimizing exposure to oxidized lipid products.

Additionally, prolonged heating degrades essential fatty acids like omega-3s, diminishing their anti-inflammatory and neuroprotective roles¹⁶. Ensuring cold processing and oil fortification may help preserve PUFA integrity.

This diagram presents the biochemical sequence of lipid peroxidation, initiated when Unsaturated Fatty Acids (UFAs) in food matrices or cellular membranes undergo oxidative attack. The process begins with the abstraction of a hydrogen atom from a UFA by a free radical, forming a lipid radical. This radical reacts with molecular oxygen to form a lipid peroxy radical, which further propagates the chain reaction by attacking adjacent lipids, ultimately generating lipid hydroperoxides. Decomposition of these unstable compounds produces secondary toxic metabolites such as malondialdehyde (MDA) and 4-Hydroxynonenal (4-HNE). These aldehydes can form covalent adducts with proteins, nucleic acids, and phospholipids, leading to oxidative stress, inflammation, and cellular dysfunction¹⁴⁻¹⁶.

Protein denaturation, digestibility, and allergenicity: Processing alters protein conformation, affecting both digestibility and antigenicity. While thermal denaturation may enhance enzymatic breakdown, excessive heating leads to aggregation and reduced solubility¹⁷. Maillard-type conjugation between proteins and sugars can impair amino acid availability and form immunogenic compounds¹⁷.

Non-thermal methods like fermentation and enzymatic hydrolysis can reduce protein allergenicity by breaking down allergenic epitopes¹⁸. On the other hand, excessive processing may produce new antigenic determinants (neoallergens), raising the risk of food sensitivities, especially in children.

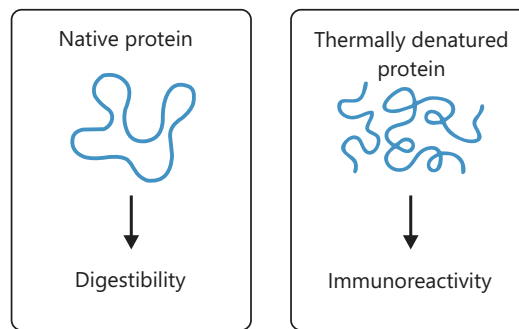


Fig. 4: Comparison of native and thermally denatured proteins in terms of digestibility and immunoreactivity¹⁷⁻¹⁹

Figure 4 contrasts the physiological properties of native proteins with thermally denatured proteins in terms of digestibility and immunogenic potential. Native proteins maintain structured conformations that are enzymatically accessible but may also retain intact epitopes that trigger immune responses. Upon heating, proteins undergo denaturation, exposing or aggregating peptide chains, which can either enhance or reduce digestibility depending on the extent of structural unfolding. Moderate denaturation often improves enzymatic hydrolysis, while excessive heat can cause aggregation, leading to lower solubility and digestibility. Additionally, thermal modification can alter protein immunoreactivity, potentially destroying allergenic epitopes or, conversely, creating neoantigens with new immune activation potential¹⁷⁻¹⁹.

Figure 4 visually supports the discussion by illustrating the biochemical differences between native and thermally altered proteins in terms of their digestive fate and allergenic profile. Native proteins are generally more digestible due to preserved tertiary structures, but may provoke immune responses when allergenic epitopes are exposed. In contrast, thermal denaturation disrupts protein folding, which may reduce allergenicity but can also cause aggregation that inhibits enzymatic access and lowers overall digestibility^{18,19}. This duality is important for understanding how food processing affects nutrient availability and allergen risk in functional and therapeutic food applications¹⁹.

Micronutrient degradation and bioavailability challenges

Thermal loss of vitamins: Heat-sensitive vitamins such as vitamin C, folate, and thiamine are especially prone to degradation during boiling, sterilization, and microwave heating²⁰. Fat-soluble vitamins (A, D, E, K) are more stable but may be lost with fat removal during low-fat food production²¹.

Figure 5a enhances the discussion by visually demonstrating the differential effects of thermal food processing techniques on vitamin stability²². As shown, vitamins C and B1, which are water-soluble and heat-labile, experience significant degradation during boiling and frying, largely due to leaching into cooking water and oxidative stress²³. In contrast, steaming and microwaving, which use less water and shorter heating durations, retain higher nutrient levels²⁴. These findings reinforce the importance of selecting nutrient-preserving cooking methods to counteract vitamin losses prevalent in ultra-processed foods, as frequently reported in the literature²⁵.

Retention of vitamins A, C, D, and B1 varies with cooking method. Steaming preserves the most nutrients, followed by microwaving, while boiling and frying lead to significant losses. Water-soluble vitamins (C and B1) are most affected by boiling due to leaching and high heat. Choosing appropriate cooking methods helps maintain optimal micronutrient bioavailability²³⁻²⁵.

Mineral bioavailability and complexation: Minerals such as iron, zinc, and calcium are affected by processing-induced changes in food matrix composition. Leaching during blanching and binding to phytic acid during extrusion reduce mineral bioaccessibility²⁶.

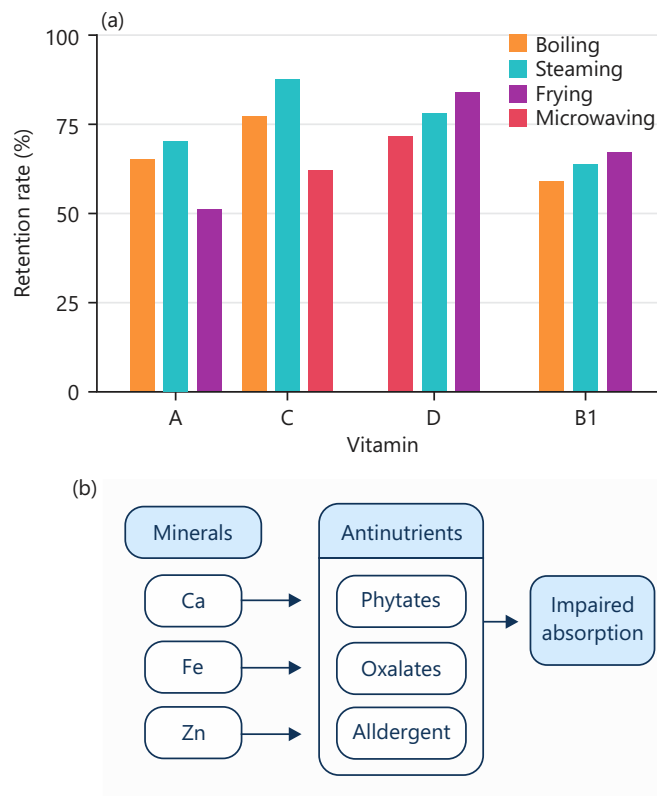


Fig. 5(a-b): (a) Comparative retention of vitamins under different cooking methods and (b) Schematic representation of mineral-antinutrient interactions leading to impaired absorption²³⁻²⁸

Figure 5b complements by visually demonstrating the mechanistic pathway through which antinutrients reduce mineral bioavailability. It highlights the molecular interactions between dietary minerals and compounds such as phytates and oxalates, resulting in the formation of insoluble complexes that hinder absorption in the gastrointestinal tract. These effects are particularly pronounced in minimally processed grains and cereals, where these antinutrients are retained, emphasizing the need for appropriate food processing or mineral absorption enhancers²⁷. Chelating agents and enhancers like ascorbic acid can improve mineral uptake in fortified processed foods²⁸.

Figure 5 illustrates how essential dietary minerals, Calcium (Ca), Iron (Fe), and Zinc (Zn), can form insoluble complexes with common antinutrients such as phytates and oxalates found in plant-based foods. These complexes significantly reduce the bioavailability of the minerals by limiting their solubility and accessibility for intestinal absorption. Phytates, prevalent in whole grains and legumes, strongly chelate divalent cations like Fe^{2+} and Zn^{2+} , while oxalates, found in leafy greens, bind calcium into insoluble calcium oxalate. These interactions can lead to nutritional deficiencies despite adequate dietary intake, especially in populations relying heavily on plant-based diets or minimally fortified foods²⁶⁻²⁸.

Impact on gut microbiota and inflammation: Highly processed diets lack fermentable substrates and are high in emulsifiers and preservatives, which can disrupt gut microbial diversity. Such dysbiosis promotes metabolic inflammation via gut barrier dysfunction and endotoxemia²⁹.

Figure 6 supports the discussion by illustrating how dietary processing level influences gut microbiota diversity and function. Diets composed predominantly of ultra-processed foods have been shown to reduce microbial richness, promote dysbiosis, and impair mucosal health factors that are linked to systemic inflammation and chronic metabolic diseases. Conversely, diets high in dietary fiber and plant-based components support the growth of commensal bacteria that produce anti-inflammatory SCFAs and reinforce gut barrier function. These changes underline the microbial mechanisms through which food processing impacts metabolic health³⁰.

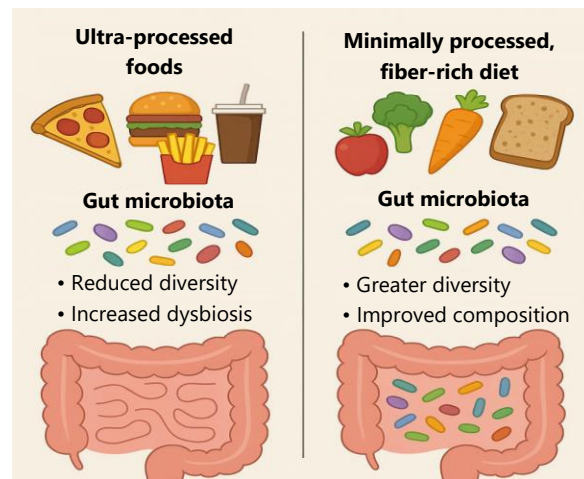


Fig. 6: Comparison of gut microbiota composition in diets rich in ultra-processed foods versus minimally processed, fiber-rich diets²⁹⁻³¹

In contrast, fermentation and whole-grain inclusion enhance Short-Chain Fatty Acid (SCFA) production, beneficial for glycemic control and anti-inflammatory pathways^{30,31}. Recent trials show that diets rich in prebiotic fibers modulate gut microbiota toward anti-obesogenic profiles³¹.

Figure 6 compares the effects of two contrasting dietary patterns on gut microbiota composition. On the left, diets dominated by ultra-processed foods characterized by low fiber, high added sugars, emulsifiers, and artificial additives are associated with reduced microbial diversity and increased dysbiosis, often marked by a higher abundance of pro-inflammatory microbial species. On the right, minimally processed, fiber-rich diets foster a more balanced gut environment, characterized by greater diversity and enhanced production of beneficial metabolites such as Short-Chain Fatty Acids (SCFAs). These microbiota changes play a critical role in metabolic regulation, immune function, and gut barrier integrity²⁹⁻³¹.

Comparative benefits of non-thermal processing: Non-thermal techniques like high-pressure processing (HPP) and pulsed electric fields (PEF) are increasingly applied to minimize nutrient losses. HPP preserves vitamins, flavors, and antioxidants without inducing thermal degradation³². These methods also reduce microbial load effectively and improve shelf life while maintaining functional compounds.

Table 1 supports the discussion by detailing how processing modality directly affects the preservation of food nutrients. Thermal processes, while effective for microbial inactivation, often compromise vitamin content, protein quality, and phytochemical stability. In contrast, non-thermal technologies like HPP and PEF are shown to better preserve labile compounds such as vitamin C, folate, and polyphenols, while maintaining mineral bioavailability and reducing the formation of undesirable byproducts³³. These findings suggest that non-thermal innovations can bridge food safety with nutritional integrity, offering a science-backed alternative to conventional thermal processing³⁴.

However, scalability and cost remain challenges for widespread application, especially in low-income settings. Further innovation in equipment and consumer acceptance is needed for mainstream integration.

Emerging biochemical insights into food processing, contaminants, and health regulation: Food processing influences human health not only by modifying nutrient composition but also through intricate biochemical interactions that extend beyond traditional concepts of nutrient degradation. Recent evidence highlights several emerging dimensions that broaden the understanding of these impacts. One critical area is the role of gut microbial metabolites, which significantly shape host immunity, neurotransmission, and energy metabolism. Processing practices that alter the availability of fermentable substrates can disrupt microbial balance and thereby influence systemic health outcomes³⁵.

Table 1: Comparative nutrient retention in foods processed using thermal and non-thermal methods

Nutrient category	Nutrient type	Thermal methods	Non-thermal methods	Citations
		(e.g., boiling, frying, pasteurization)	(e.g., HPP, PEF, cold plasma)	
Vitamins	Vitamin C	Low retention (20-50% loss)	High retention (80-95%)	Sun <i>et al.</i> ³² ,
	Vitamin A	Moderate retention, susceptible to oxidation	High retention, minimal degradation	Rifna <i>et al.</i> ³³ , and
	Folate (B9)	Highly heat-labile, significant loss in boiling	Retained in most non-thermal treatments	Ibrahim <i>et al.</i> ³⁴
Minerals	Iron	Stable under heat, bioavailability may reduce with leaching	Unaffected, matrix preserved	
	Calcium	Stable, minor loss during thermal leaching	Retained with minimal change	
Proteins	Overall structure	Denatured, may reduce solubility or digestibility	Preserved, minimal denaturation	
	Allergenicity	May reduce or create neoallergens	Can lower allergenicity through enzymatic activity	
Phytochemicals	Polyphenols	Degradation common with heat exposure	Better preserved, antioxidant activity retained	
	Carotenoids	Isomerization and oxidation reduce effectiveness	Retention improved, less exposure to oxidation	

This table summarizes the relative nutrient retention of key vitamins, minerals, proteins, and phytochemicals under thermal (e.g., boiling, frying, pasteurization) versus non-thermal (e.g., High-Pressure Processing (HPP), pulsed electric fields (PEF), cold plasma) food processing techniques. Thermal methods often lead to nutrient degradation through leaching, heat-induced denaturation, and oxidative loss. In contrast, non-thermal methods maintain food structure and minimize nutrient loss by avoiding high temperatures and preserving bioactive compounds. This comparative framework highlights the nutritional advantages of emerging, low-temperature technologies in food preservation and formulation³²⁻³⁴.

Another dimension involves the introduction of foodborne contaminants such as microplastics, frequently linked to packaging and processing methods. These compounds have been associated with oxidative stress, lipid peroxidation, and impaired nutrient utilization, compounding the risks posed by ultra-processed foods. Such contaminants may act synergistically with nutrient-depleted matrices to exacerbate metabolic dysfunction³⁶.

At the micronutrient level, processing-induced biochemical and epigenetic alterations further complicate nutritional outcomes. Mycotoxin exposure exemplifies this dual burden, simultaneously reducing nutrient bioavailability and triggering adverse molecular signaling. Targeted nutritional interventions aimed at mitigating these effects are therefore increasingly important³⁷.

Phytochemicals and bioactive compounds represent another crucial aspect. Processing can either diminish or preserve these compounds depending on the method employed, thereby modulating their antioxidant and immunoregulatory functions. The stability of these phytochemicals, alongside their interactions with the food matrix, ultimately determines their contribution to metabolic and immune resilience³⁸.

Moreover, systemic physiological processes such as sleep regulation, which are intimately linked to energy balance and metabolic homeostasis, may also be influenced by diet and processing-mediated biochemical changes. This perspective underscores the far-reaching implications of food processing on human health³⁹.

Collectively, these insights indicate that food processing research must extend beyond its conventional focus on nutrient losses to encompass microbial ecology, contaminant exposure, phytochemical integrity, and systemic biochemical regulation.

Table 2 provides a synthesized overview of these emerging biochemical pathways, outlining how microbial metabolites, microplastic contaminants, mycotoxin-induced epigenetic modifications, phytochemical stability, and sleep regulation collectively contribute to metabolic outcomes. This integration reinforces by highlighting the multifactorial nature of food processing and its systemic influence on health.

Table 2: Emerging biochemical effects of food processing beyond classical nutrient degradation

Factor	Biochemical mechanism	Health Implication	Citation
Gut microbial metabolites	Modulate immunity, neurotransmission, and energy balance	Dysbiosis vs resilience	Anih <i>et al.</i> ³⁵
Microplastics	Oxidative stress, lipid disruption	Cardiometabolic and nutrient impairment	Anih <i>et al.</i> ³⁶
Mycotoxins	Epigenetic modification, mineral binding	Reduced bioavailability, chronic disease	Anih <i>et al.</i> ³⁷
Herbal phytochemicals	Altered stability and bioactivity	Modulated immune/ metabolic defense	Chinonso <i>et al.</i> ³⁸
Sleep regulation	Neurochemical pathways influenced by diet	Systemic metabolic balance	Anih <i>et al.</i> ³⁹

An overview of new biochemical pathways affected by food processing. The table organizes current evidence into five main areas, linking each factor to its main biochemical mechanism and the health effects it causes. This organized summary highlights new aspects of food processing that go beyond just nutrient degradation

CONCLUSION

Food processing remains essential for ensuring food safety, accessibility, and shelf life in modern food systems. However, its influence on nutrient bioavailability and metabolic health is complex and often detrimental when processing is excessive or poorly managed. Emerging evidence links highly processed diets to impaired nutrient absorption, metabolic dysfunction, and chronic disease risk. The adoption of non-thermal technologies and mindful fortification strategies offers promising avenues to preserve nutritional quality. Continued research into processing-nutrient-health interactions is crucial for guiding innovation, policy, and dietary recommendations. A holistic, evidence-based approach is vital to balance technological advancement with long-term public health outcomes.

SIGNIFICANCE STATEMENT

This review provides a comprehensive synthesis of current biochemical, nutritional, and epidemiological evidence on how diverse food processing methods influence nutrient bioavailability and metabolic health. By classifying processing techniques and examining their effects on macronutrients, micronutrients, gut microbiota, and key metabolic outcomes, the work offers an integrated perspective that bridges laboratory findings with public health implications. The findings highlight both the risks associated with excessive processing and the potential of moderate and non-thermal technologies to preserve nutritional integrity. This evidence is highly relevant for guiding food industry practices, informing nutrition policy, and shaping dietary recommendations aimed at reducing the burden of diet-related chronic diseases.

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