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Food chemistry and nutrient bioavailability: Bridging science and human nutrition

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Abstract
Nutrient bioavailability is the proportion of an ingested nutrient that is digested, absorbed, and metabolically available for physiological functions. Understanding how food chemistry the composition, structure and transformations of food interacts with human physiology is essential to improving nutritional outcomes. This review synthesizes current knowledge on (1) how the food matrix and processing influence bioaccessibility and bioavailability; (2) chemical and physical factors (anti-nutrients, enhancers, molecular form) that modulate uptake; (3) methods to assess bioavailability; (4) technological approaches (fortification, encapsulation, processing strategies) to enhance delivery; and (5) the emerging role of the gut microbiome and systems-level modeling. This article highlights persistent challenges and proposes directions to better connect mechanistic food-chemistry research with practical nutrition strategies.

Keywords: Food matrix, bioaccessibility, bioavailability, nutrition, fortification, encapsulation

1. Introduction

Human nutrition depends not just on the amount of nutrient present in foods, but on how much of that nutrient becomes available to the body after ingestion (bioavailability) (Stevenson, 2006) [40]. The chemical form of a nutrient (e.g., heme vs. non-heme iron), its molecular interactions in the food matrix, the presence of inhibitors or enhancers, processing history, and host factors (digestion, microbiome, physiology) all determine ultimate nutritional value (Xing *et al.*, 2022) [46]. Food chemistry provides the mechanistic basis for these interactions and offers levers through formulation or processing to improve nutrient delivery (Zhang *et al.*, 2025) [50]. Recent reviews emphasize that the food matrix concept must be central to dietary guidance and product design because matrix-mediated interactions can substantially alter bioaccessibility and bioefficacy.

2. Key concepts: bioaccessibility vs. bioavailability

- Bioaccessibility refers to the fraction of a nutrient released from the food matrix in the gastrointestinal tract and made available for absorption (Santos *et al.*, 2019) [36].
- Bioavailability is the fraction of the ingested dose that is absorbed and reaches systemic circulation in an active form (Paul, 2019) [26].

Distinguishing these is critical because many food-chemistry interventions improve bioaccessibility without necessarily enhancing absorption or systemic utilization (which may be limited by transporters, first-pass metabolism, or microbial transformation). Quantifying each step requires complementary analytical and biological methods (Fennema *et al.*, 2017) [10].

3. Food matrix effects chemistry in context

The "food matrix" describes the structural and compositional context in which nutrients reside (proteins, lipids, carbohydrates, fibres, and other bioactives) (Aguilera, 2019) [1]. Matrix components affect solubility, release during digestion, and physical accessibility to enzymes and uptake transporters (Dima *et al.*, 2020) [8]. For example, carotenoids are fat-soluble and their micellarization during digestion depends strongly on lipid presence and particle size; calcium and iron availability may be reduced by binding to oxalates or phytates in certain matrices (Corte-Real and Bohn, 2018) [6]. Dairy matrices illustrate that the whole food can have different health effects than isolated nutrients because proteins, lipids and minerals interact synergistically or antagonistically (Aguilera, 2019) [1]. Because matrix interactions are complex and often compound-specific, food-chemistry characterization (particle size, lipid phase, binding affinities) is a prerequisite to predict bioaccessibility (Peyron *et al*., 2018) [29].

4. Processing: a double-edged sword

Food processing alters chemical and physical structure sometimes improving, sometimes reducing bioavailability (Ribas-Agustí *et al*., 2018) [33]. Thermal treatments can denature proteins (improving digestibility), but may degrade heat-labile vitamins (e.g., vitamin C, B vitamins). Cooking of carotenoid-rich vegetables increases carotenoid bioaccessibility by disrupting cell walls, while boiling leafy greens can leach water-soluble vitamins (Bhat *et al*., 2021) [2]. Fermentation often enhances micronutrient availability by degrading phytates and producing bioactive metabolites (Samtiya *et al*., 2021) [35]. Advanced processing (high-pressure, extrusion, enzymatic hydrolysis) can be tailored to increase release of target nutrients from the matrix; however, processing can also generate undesirable compounds or complex the nutrient with other food components, reducing uptake (Aguilera, 2019) [1]. Thus, processing must be considered as a tunable variable rather than simply “good” or “bad.”

5. Chemical modulators: inhibitors and enhancers of absorption

- **Inhibitors:** Phytates, oxalates, certain polyphenols and dietary fibres can chelate minerals (e.g., Fe, Zn, Ca) and reduce their intestinal uptake (Zhang *et al*., 2022) [46]. Tannins can bind proteins and digestive enzymes, decreasing protein digestibility (Cirkovic Velickovic and Stanic-Vucinic, 2018) [5].
- **Enhancers:** Vitamin C enhances non-heme iron absorption by reducing Fe (III) to Fe (II) and forming soluble complexes (Pan *et al*., 2024) [25]. Dietary lipids improve micelle formation required for carotenoid and fat-soluble vitamin absorption. Certain fermentation products (organic acids) can improve mineral solubility. Understanding stoichiometry and kinetics of these chemical interactions within the gut environment is critical to predict net effects (Hsu *et al*., 2019) [13].

6. Methods to assess bioavailability: strengths and limitations

- ***In vitro* digestion models** (static or dynamic gastrointestinal simulators) estimate bioaccessibility and micellarization under controlled conditions; they are useful for screening but lack host absorption processes (Gonçalves *et al*., 2021) [11].
- **Ex vivo and cell culture models** (e.g., Caco-2 intestinal cells) test transport and cellular uptake but cannot fully capture whole-body kinetics or microbial interactions (Pearce *et al*., 2018) [27].
- ***In vivo* human studies** remain the gold standard (isotopic tracers, balance studies, clinical biomarkers), but are costly and ethically constrained (Penner *et al*., 2009) [28].
- **Mathematical modeling and prediction algorithms** are emerging to integrate physicochemical data and experimental results into bioavailability estimates; standardization and validation remain active needs. Recent guidance proposes frameworks for harmonized prediction equations and reporting to improve comparability across studies (Soliman *et al*., 2022) [38].

7. Technological strategies to improve nutrient delivery

7.1 Fortification and chemical form selection

Selecting more bioavailable chemical forms (e.g., ferrous fumarate vs. elemental iron) and matching fortificant carriers to the food matrix reduces antagonistic interactions. Fortification success also requires consideration of sensory changes and stability (Mattar *et al*., 2022) [21].

Fortification is one of the most widely applied strategies to combat micronutrient deficiencies, but its success largely depends on the chemical form of the nutrient selected (Dwyer *et al*., 2015) [9]. The stability, solubility, and interaction of the fortificant with the food matrix determine both sensory quality and bioavailability (Lavelli *et al*., 2021) [17]. For example, ferrous fumarate and ferrous sulfate are preferred for iron fortification due to higher solubility and absorption compared with elemental iron, although they may cause color and flavor changes in certain foods (Hurrell, 2002) [14]. Similarly, zinc sulfate is commonly used over zinc oxide because of greater bioavailability in aqueous systems (Wedekind *et al*., 1992) [45]. The choice of vitamin form also matters; vitamin A is typically fortified as retinyl palmitate for stability in oils, while vitamin D is added in fat-soluble forms that integrate better into lipid matrices, enhancing absorption (Maurya *et al*., 2022) [22]. Careful selection must balance nutritional efficacy, chemical compatibility, sensory attributes, and cost-effectiveness (Rajasekaran and Kalaivani, 2013) [30]. Moreover, matching fortificants to specific dietary staples of target populations ensures optimal delivery and minimizes inhibitors such as phytates or tannins, ultimately making fortification a science-driven intervention for improving public health nutrition (Osendarp *et al*., 2018) [24].

7.2 Encapsulation and delivery systems

Micro- and nano-encapsulation protect labile nutrients from degradation, mask off-flavors, and enable controlled release at target gut locations improving stability and sometimes absorption (Samakradhamrongthai, 2024) [34]. Advances in food-grade nanoparticles, liposomes, protein- or polysaccharide-based carriers, and pH-responsive release systems have shown promise for vitamins, polyphenols, and omega-3 fatty acids (Mankan *et al*., 2025) [19]. Regulatory, safety, and scale-up considerations remain key barriers to widespread food application (Rashidinejad, 2024) [31].

7.3 Processing optimization and ingredient pairing

Combining ingredient science (e.g., adding small amounts of oils to vegetable mixes to aid carotenoid uptake, co-formulating vitamin C with plant-based iron sources) and tailored processing (mild thermal treatment, enzymatic phytase treatment) can markedly improve net nutrient availability while maintaining sensory quality (Hofmann *et al*., 2020) [12].

8. The gut microbiome as a mediator of nutrient fate

The gut microbiota acts as a metabolic “organ” that transforms dietary components, synthesizes vitamins, modifies bile-salt mediated lipid digestion, and influences mineral solubility (Vernocchi *et al.*, 2020) [42]. Microbial fermentation of fibres yields short-chain fatty acids that modulate intestinal physiology and nutrient transporter expression (Wang *et al.*, 2019) [43]. Moreover, the microbiome can convert some polyphenols into more or less absorbable metabolites (Marín *et al.*, 2015) [20]. Recent systemic reviews and mechanistic studies underline that inter-individual microbiome differences can contribute to variability in nutrient responses to identical diets, suggesting a role for personalized nutrition strategies informed by microbiome profiling (Lampe *et al.*, 2013) [16].

9. Translating food-chemistry knowledge into public-health nutrition

Bridging mechanistic science and population nutrition requires: (a) robust, standardized methods to measure bioavailability across matrices and populations; (b) context-aware fortification/processing strategies appropriate for local diets; and (c) policies that consider not only nutrient content but expected bioavailable fraction. For instance, staple food fortification programs should be designed with matrix and inhibitor considerations in mind and validated by bioavailability studies in target populations rather than assuming uniform uptake. Modeling frameworks that combine food composition, processing data, and physiological factors can improve policy decisions and predict population-level impacts (Sanz *et al.*, 2025) [37].

10. Challenges and future directions

1. **Standardization and comparability:** Diverse *in vitro* methods and inconsistent reporting hamper cross-study synthesis. Community-wide standards for assay design, reporting and validation would accelerate progress (McMullen *et al.*, 2019) [23].

2. **Bridging scales:** Integrating molecular-level chemistry with whole-organism outcomes (PK/PD, biomarkers) remains difficult; multi-scale models and better translational studies are needed (Kuepfer *et al.*, 2012) [15].

3. **Personalization:** Accounting for host genetics, age, disease status, and microbiome composition could improve nutrient recommendations but will require large, well-characterized cohorts (Bianchetti *et al.*, 2023) [3].

4. **Safe application of new technologies:** Nanoencapsulation and other advanced delivery systems show efficacy in controlled studies, but long-term safety, regulatory frameworks, and consumer acceptance must be addressed prior to widespread adoption (Soni *et al.*, 2022) [39].

Table 1: Influence of Food Chemistry and Processing on Nutrient Bioavailability

Nutrient / Compound	Food Source	Key Food Chemistry Factor	Effect on Bioavailability	Reference
Iron (non-heme)	Cereals, legumes	Presence of phytates and tannins	Strong reduction in intestinal absorption	Zhang *et al.*, 2024 (Food Chemistry) [47]
Iron (non-heme) + Vitamin C	Plant-based foods	Ascorbic acid reduces Fe^{3+} to Fe^{2+} and forms soluble complexes	Marked increase in absorption	Zhang *et al.*, 2022 (Nutrients) [48]
Calcium	Spinach, green leafy vegetables	Binding with oxalates	Low bioavailability (<10%) despite high calcium content	Toydemir *et al.*, 2022 (Foods) [41]
Carotenoids (β-carotene, lycopene)	Carrots, tomatoes	Heat processing disrupts cell wall; lipids aid micelle formation	Increased bioaccessibility after cooking, especially with added oil	Zheng *et al.*, 2022 (CRFSFS) [51]
Polyphenols (flavonoids)	Tea, cocoa	Complexation with proteins and fibres	Decreased absorption and bioefficacy	Zhang *et al.*, 2024 (Food Chemistry) [47]
Vitamin B12	Dairy and meat matrix	Stable binding to proteins; requires gastric release and intrinsic factor	High bioavailability (~50-60%) from animal sources	Weaver *et al.*, 2025 (Critical Reviews in Food Science & Nutrition) [44]
Omega-3 fatty acids	Fish oils, fortified foods	Encapsulation in nanoemulsions	Improved stability and intestinal uptake	Lei *et al.*, 2024 (Frontiers/MDPI) [18]
Minerals (Zn, Fe)	Fermented cereals	Phytase activity during fermentation	Increased mineral solubility and absorption	Toydemir *et al.*, 2022 (Foods) [41]
Vitamin D	Fortified dairy	Fat matrix facilitates absorption	Higher serum response vs. supplements in water-based matrices	Cifelli *et al.*, 2021 (Nutrients) [4]

Conclusion

Food chemistry provides essential mechanistic understanding to predict and improve nutrient bioavailability. Matrix composition, processing, chemical interactions, delivery technologies and the gut microbiome all interact to determine the nutritional value of foods. Progress requires integrated approaches standardized assays, translational human studies, systems modeling, and responsible technological deployment to convert lab discoveries into measurable improvements in public health nutrition. Collaborative efforts across food chemists, nutritionists, microbiologists, and policy makers will be necessary to close the gap between nutrient content and nutrient benefit.

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