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Perspective

Perspective: Nutrient bioavailability is the missing ingredient connecting food systems to nutrition security and environmental sustainability

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ABSTRACT

Increasing attention has focused on the capacity of current global food systems to provide accessible, affordable, and sustainable food to a growing human population, particularly amid ongoing climate and environmental changes. Concerns about the dysfunction of the global food system have led to the development of several initiatives to estimate current and predict future global nutrient supplies based on various climate, production, and demand scenarios. Yet none adequately accounts for differences in nutrient bioavailability across food groups. As nutrient bioavailability varies substantially between plant-source foods (PSFs) and animal-source foods (ASFs), accounting for these differences has important implications for global nutrient supplies and the environmental costs associated with their production. In this perspective, we highlight the variability in estimated bioavailabity across PSFs and ASFs for 27 key nutrients and the limited accounting for bioavailability in major studies and nutrition recommendations. We conclude with a discussion of current best practices, highlighting avenues for future research to account for bioavailability and to more accurately evaluate and propose nutritionally adequate diets. This perspective suggests that, although existing data limitations should not preclude food systems researchers from accounting for bioavailability, a concerted effort is needed to develop more consistent and representative estimates of bioavailability across a variety of nutrients.

Keywords: sustainable food systems, food systems modeling, bioavailability, Planetary Health Diet, nutrient absorption

Introduction

The global food system accounts for one third of total anthropogenic greenhouse gas emissions [1]. Each year, new research also highlights the hazards awaiting an increasingly interconnected global food system, vulnerable to rapidly increasing climate and environmental change [2]. For example, in 2022, global food supplies were heavily disrupted by the culmination of the “3 C’s”: climate change, COVID-19, and conflict, leading to price volatility and food insecurity, especially in low- and middle-income countries (LMICs) [3,4]. Food production is a primary contributor to global environmental degradation [5], which has led to calls for the development of sustainable farming practices [6–8] and dietary recommendations advocating for diverse intake of minimally processed plant-based foods and moderate or partial replacement of animal-source foods (ASFs) to improve resource efficiency and human cardiometabolic health [9,10]. However, a key limitation of this research is its partial or inaccurate accounting of nutrient bioavailability, defined as the proportion of a nutrient that becomes physiologically available [11], which creates uncertainties about the benefits of certain diets as it relates to micronutrient nutrition. Without accounting for bioavailability differences between (and

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Abbreviations: ASF, animal-source food; EFSA, European Food Safety Authority; GI, gastrointestinal; HICs, high-income countries; LMICs, low- and middle-income countries; PSF, plant-source food.

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within) foods, which can vary significantly across individual biological characteristics and nutrient sources, the research on which food system recommendations are based may provide incorrect estimates of global nutrient supplies.

In this perspective, we highlight differences in nutrient bioavailability between ASFs and plant-source foods (PSFs) as a crucial yet often-overlooked methodological component of food systems research. We introduce the interrelated factors that determine a nutrient's bioavailability, present estimated bioavailability for ASFs and PSFs across 27 nutrients, discuss examples of studies and guidelines and their approaches to accounting for bioavailability, and conclude with a focus on current best practices and future directions for incorporating bioavailability into food systems research.

Nutrient Bioavailability and Absorption

Nutrient bioavailability is defined as the measure of the total amount of nutrients in a given food that can be digested, absorbed, metabolized, and stored in the body [12]. Thus, bioavailability represents the proportion of a nutrient that becomes physiologically available [13]. The factors that determine bioavailability are complex and can be divided into person-specific and food-specific categories (Figure 1) [14]. Person-specific factors include age, sex, baseline nutritional status, developmental requirements (e.g., infancy, adolescence, pregnancy, and lactation), chronic environmental enteric dysfunction, and gut microbiome composition [15–18]. The food-specific category includes characteristics of the food matrix (the physical and chemical structure of foods), methods of preparation (such as fermentation), and accompanying foods that can enable or inhibit absorption [13,19–21].

Two key challenges that limit the inclusion of bioavailability in food systems research are as follows: *1*) the complexity of interrelated factors that determine absorption and *2*) the inconsistency in its definition and use of related terms. Accurately measuring bioavailability in the body is difficult because effectively accounting for the interconnected factors (Figure 1) that determine absorption is not always possible. The Miller equation, e.g., estimates zinc absorption as a function of dietary intake of both zinc and phytate, a known inhibitor of zinc and other micronutrients [22]. However, this approach is limited to nutrients such as zinc, for which there are few known interacting factors that affect bioavailability. The second challenge impeding the inclusion of bioavailability in food systems research is the reliance on closely related measures in the absence of bioavailability estimates [15]. Bioaccessibility, bioconversion, and bioefficacy are highly related terms that capture different aspects of absorption. Bioaccessibility is the proportion of a nutrient that is made accessible for intestinal absorption; bioconversion is the proportion of a nutrient that is converted to its active form; and bioefficacy is the proportion of a nutrient that has a measurable nutritional effect [23]. For example, bioavailability of amino acids is often based on digestibility, a measure of intestinal absorption that does not capture the role of gut metabolism but is commonly used in clinical and preclinical studies [24,25]. One significant consideration is that each of these highly related measures uses different assessment methods, ranging from in vivo human studies to ex vivo animal models and in vitro hybrid models,

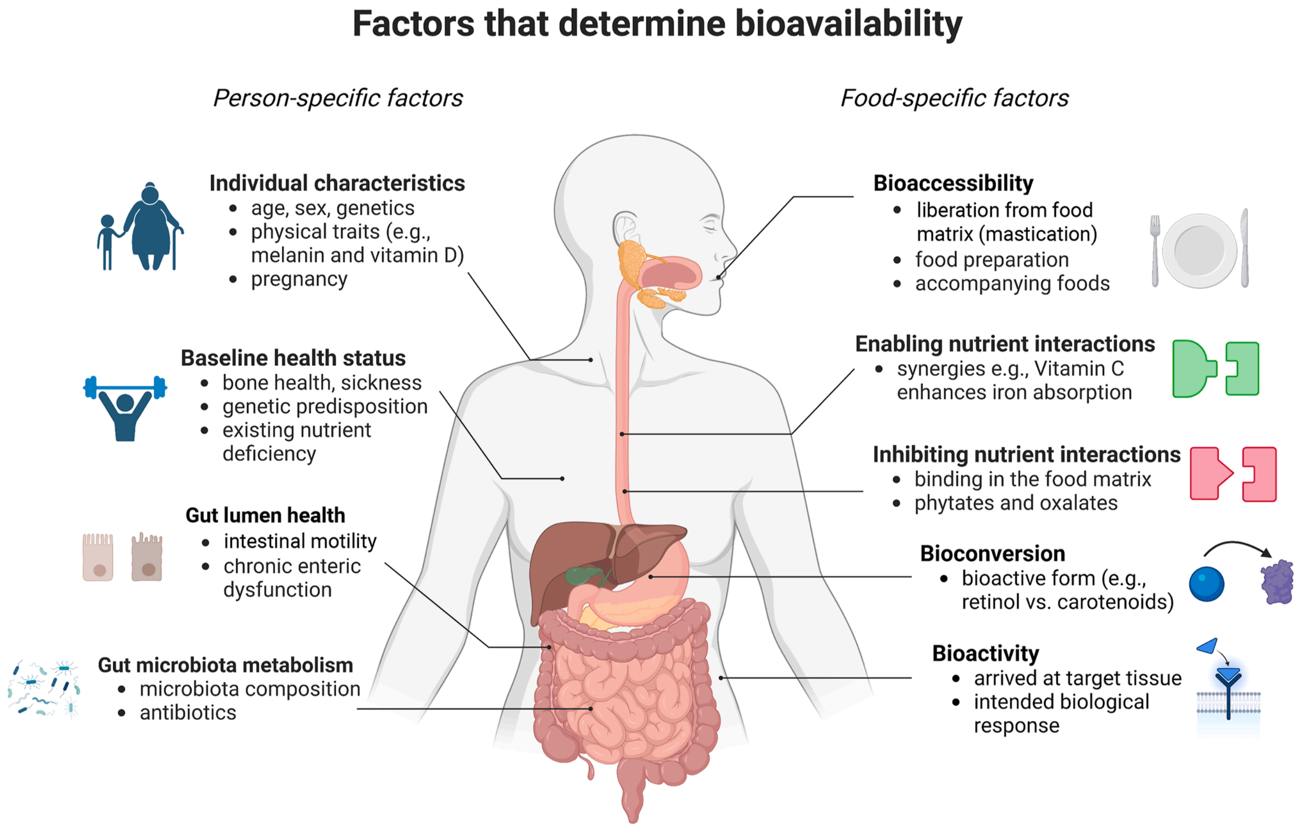

FIGURE 1. Factors that determine bioavailability. Bioavailability is determined by individual-level characteristics related to genetics and body composition, as well as food-level characteristics such as nutrient interactions. Original figure produced using BioRender.

each of which may model the oral, gastric, and/or intestinal phases of digestion and absorption [26,27]. Across these approaches, there is growing recognition of the efficacy of isotopic human tracer studies (when appropriate sensitivity levels and tracers for a given nutrient exist) in providing accurate bioavailability estimates for humans [28].

As nutrients interact with a host of individual- and food-specific factors throughout digestion, absorption, metabolism, and storage, bioavailability studies allow a more comprehensive assessment of a food's ability to support human health than nutritional content alone [23]. For example, an analysis of isotopic human tracer studies showed that calcium absorption from plant-based sources is ~26% lower than from animal-based sources due to inhibitory acids, such as oxalates and phytates, in plant-based foods [29]. Even within a single food source, such as cow's milk, binding proteins that facilitate vitamin B_{12} bioavailability can vary by animal breed and geographic region [30]. Relatedly, chemical structure also shapes bioavailability, as seen with fortification, which is credited with large reductions in the global prevalence of micronutrient deficiency [31]. For example, the absorption of ferrous sulfate, a cheaply available form of iron fortification, is $\leq$4 times lower than that of its more expensive analog, sodium ferredate, which is resistant to inhibitors such as phytate [32]. In short, although gross nutrient content and in vitro studies can provide important indicators of how a food source may support biological functioning, the complex nature of the individual, technical, and environmental determinants of bioavailability demands an equally complex, holistic approach to their consideration within food systems research.

To capture this complexity, a variety of research models can be used to investigate distinct elements of the bioavailability pathway [33]. Bioaccessibility can be assessed by static (or biochemical) models, in which the product of 2 to 3 digestion steps is held largely immobile in a single static bioreactor [34], as well as by dynamic models that better reflect the chemical, physical, and biochemical conditions within the gastrointestinal (GI) tract [35]. Different nutrients are absorbed in different parts of the GI tract, and in vitro human cell line models can simulate the cellular conditions (e.g., cell barriers and shear stress) of digestive stages to study nutrient transport and reactions [36].

Once these nutrients are made bioaccessible and absorbed, they must be metabolized, and bioavailability studies can draw on pharmaceutical research that measures the clearance of administered compounds [37]. In vivo human studies measuring bioavailability based on excretion may not always capture this metabolism, as biological factors, such as declining kidney function with age, may falsely indicate poor absorption while intestinal absorption remains normal [38]. Finally, to investigate bioactivity or the biological response to a nutrient as it is metabolized and distributed to target organs [23], bioavailability research uses in vitro biomarkers and ex vivo models of organs and tissues under laboratory conditions [33].

Given this complexity, it is crucial for food systems researchers to understand the contributions of nutrient bioavailability in quantifying nutrient supplies and dietary intake to inform sustainable recommended amounts of global ASF and PSF consumption. To be clear, this perspective does not advocate pivoting these recommendations, but rather that an accurate accounting of bioavailability would strengthen the nutrient supply and adequacy estimates on which they are based.

Estimated Bioavailability for Select Nutrients From PSFs and ASFs

Current bioavailability estimates for 27 nutrients found in ASFs and PSFs are sourced from the NIH Office of Dietary Supplements Fact Sheet for Health Professionals and from a recent peer-reviewed compilation of food source-specific bioavailability estimates [39,40]. These 27 nutrients are compared using the ASF- and PSF-estimated bioavailabilities in Figure 2. These sources were used because there is currently no existing database that provides nutrient-specific bioavailability estimates for ASFs and PSFs. The estimated bioavailability for 13 of the nutrients was derived from the NIH Office of Dietary Supplements Fact Sheet for Health Professionals, which summarizes evidence from peer-reviewed scientific literature and is updated annually for each nutrient [39]. The estimates for the remaining 14 nutrients were sourced from a recent review by Chungchunlam and Moughan [40], the largest and most recent peer-reviewed compilation of food source-specific bioavailability estimates.

Across all nutrients naturally found in both ASFs and PSFs [i.e., excluding β-carotene, which is derived from plant pigments [41], and retinol (preformed vitamin A) and vitamin B_{12}, which are only naturally found in ASFs [41,42]], bioavailability in ASFs is higher or equivalent to that in PSFs for all but 3 nutrients (riboflavin, vitamin C, and vitamin K as phylloquinone). Although differences in food source between nutrients such as zinc and iron are well-documented in the literature [43], the differences in estimated bioavailability are especially notable for biotin, which is 69% more bioavailable in ASFs than in PSFs, as well as phosphorus and pantothenic acid, with 20% and 30% greater bioavailability, respectively.

The estimated bioavailability in Figure 2 does not reflect the absolute nutrient content of foods, because PSFs may provide a greater absolute amount of certain nutrients than ASFs, and vice versa. Further, researchers should not distinguish between ASFs and PSFs solely based on their absolute nutrient content, but rather recognize the complementarity of their nutrient profiles and the synergistic roles they play in sustainable, healthy diets in LMICs and high-income countries (HICs) [44].

Importantly, estimated bioavailability estimates (i.e., specific values) do not capture the full variability in nutrient bioavailability within specific foods. As there are nutrients for which bioavailability data are lacking for both ASFs and PSFs [14,39], further research is needed to better assess nutrient bioavailability across dietary sources and to understand the interactions among factors that influence absorption. Another limitation of estimated bioavailability is the wide range in bioavailability (even within ASF or PSF categories), depending on the food. For example, carotenoid bioavailability has been estimated to range from 2:1 for β-carotene in oil to 77:1 in raw carrots [45]. Additionally, the proportion of iron that is heme iron ranges from ~25% in chicken and fish to ~75% in ruminant meat [46]. Accounting for intracategory nuances within individual foods is imperative when estimating bioavailability at the food-group level and represents an important avenue for future research. Accounting for bioavailability in a context-specific manner (e.g., for a specific country or region) would ideally capture physiological determinants that align with a population's demographic composition, including regional dietary patterns and preferences, associated gut microbial compositions, and interactions among commonly consumed nutrients.

Although there is insufficient data across a broad enough array of nutrients to facilitate such a comprehensive accounting, this perspective is not intended solely to stress the absence of crucial bioavailability data and the need for concerted research in this area. Despite this knowledge gap, there are best practices that can be applied to account for bioavailability differences to facilitate meaningful avenues forward and greatly strengthen the utility of food systems research,

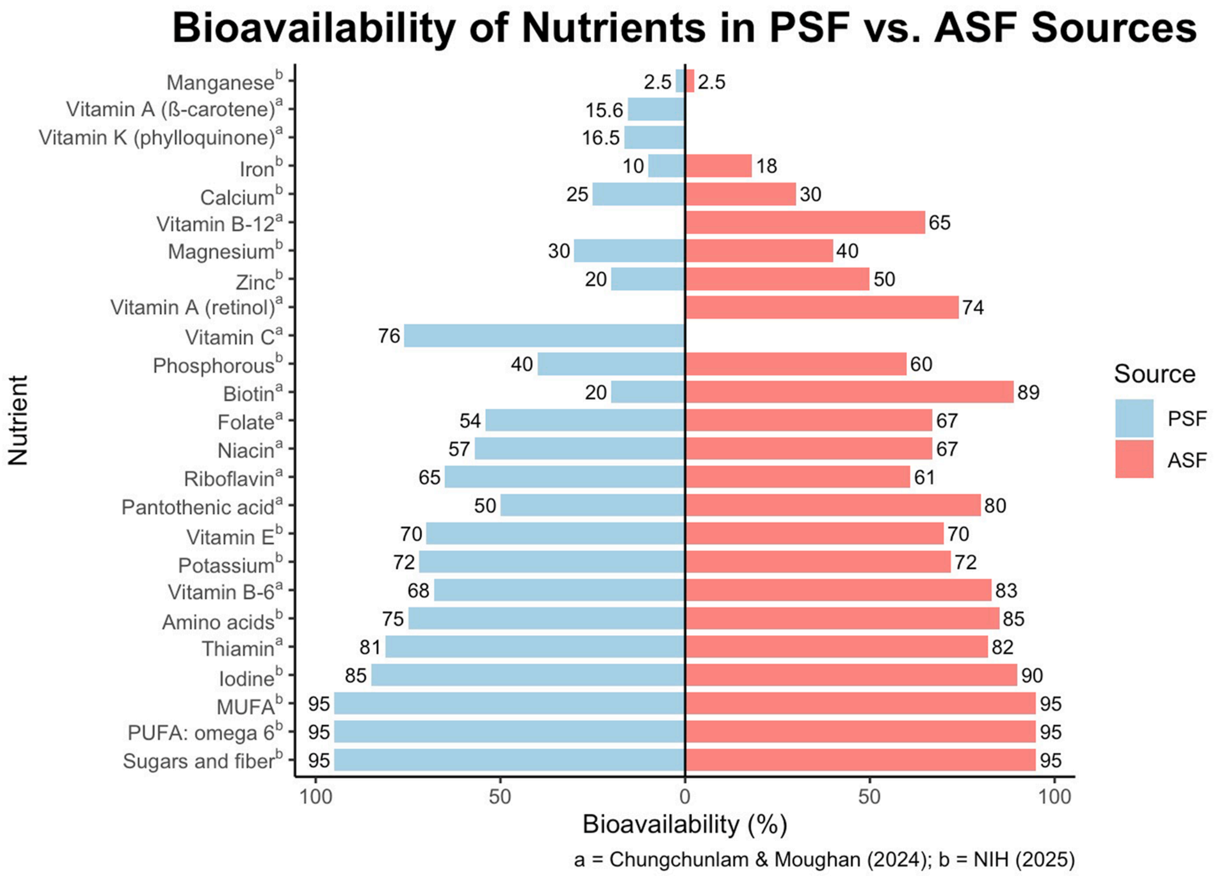

FIGURE 2. Bioavailability of selected nutrients in plant-source foods (PSFs) compared with animal-source foods (ASFs). Across key nutrients, bioavailability estimates can vary significantly between PSFs and ASFs, underscoring the need for food systems research to meaningfully account for these differences. Nutrients listed with zero bioavailability (i.e., β-carotene, phylloquinone, and vitamin C for animal-based sources and vitamin B12 and retinol for plant-based sources) may reflect negligible quantities in the respective PSFs or ASFs, rather than no bioavailability.

especially for projects that predict nutrient supply and adequacy, as highlighted in the subsequent section.

Current Approaches to Account for Bioavailability

Existing food systems approaches stand to benefit from integrating bioavailability estimates throughout the research process, providing a clearer, more detailed picture of dietary outcomes. For nutrients such as vitamin A, the difference in bioavailability between ASFs and PSFs is reflected in the food composition tables themselves through biochemical conversion factors (e.g., vitamin A retinol activity equivalents to standardize between ASF retinols and PSF carotenoids) [47]. For other nutrients, bioavailability can be accounted for in the development of dietary guidelines based on nutrient requirement estimates from organizations such as the WHO and the European Food Safety Authority (EFSA). A dietary reference value is based on the evaluation of evidence for the link between nutrient intake and a biomarker or health outcome. Nutrient recommendations are set using one of the following designs: a factorial approach (e.g., iron), null balance design (e.g., protein and zinc), or biomarker concentrations associated with adequate stores (e.g., vitamin A, vitamin D, folate, and iodine) [48]. Bioavailability can often be incorporated into the factorial design and null balance.

As models adapt to current diets, dietary shifts that affect bioavailability would most likely affect the intake required to achieve a certain biomarker concentration. One example is that the WHO zinc recommendation is given for diets with high (50%), moderate (30%), and low (15%) zinc bioavailability based on phytate intake (i.e., high PSF reliance) and protein content, whereas the EFSA considers phytate concentrations of 300, 600, 900, and 1200 mg/d, which represent intakes observed in European populations [49,50]. Accordingly, the WHO provides several recommendations on zinc bioavailability that depend on the phytate and protein content of the regional diet, whereas recommendations based solely on traditional Western diets are not adapted to differences in bioavailability across the whole diet. When designing scenarios for a healthy diet within planetary boundaries (e.g., increasing relative consumption of PSFs in countries with high ASF consumption), bioavailability estimates must account for the effects of these diets on nutrient bioavailability.

Establishing nutrient requirements as a foundation for food-based dietary guidelines across countries is an important entry point for considering bioavailability across different dietary types. Current nutrient recommendations (e.g., from the National Academies of Sciences, Engineering, and Medicine, the EFSA, and the Nordic Nutrition Recommendations consider bioavailability differences between PSFs and ASFs mainly for iron, zinc, folate, and vitamin A, but

TABLE 1

Examples of bioavailability assumptions in major studies and dietary guidelines

Nutrition recommendation	Design	**Nutrient bioavailability included**
WHO [49]	Establishment of nutrient requirements to be used as foundation for developing food-based dietary guidelines in different countries.	Iron, zinc, folate, and vitamin A.
EFSA [50]	Establishment of nutrient requirements to be used as foundation for, e.g., developing food-based dietary guidelines in the EU.	Iron, zinc, iodine, folate, and vitamin A.
NASEM [51]	Establishment of nutrient requirements to be used as foundation for developing food-based dietary guidelines in the United States and Canada.	Iron, folate, and vitamin A.
NNR [52]	Establishment of nutrient requirements to be used as foundation for developing food-based dietary guidelines in the Nordic and Baltic countries.	Iron, zinc, and vitamin A.
Study	**Design**	**Bioavailability assumptions**
IFPRI's IMPACT (2015–present) [53]	Designed for scenario analysis within agriculture. The core model includes climate, water, crop simulation, value chain, land use, nutrition and health, and welfare analysis.	Not included. In the upcoming updates, nutrient deficiencies will be addressed, and bioavailability will be relevant.
GENuS (2016) [54]	Estimates nutrient supply for several population groups, based on FAO food balance sheets (amount of food) and food consumption data. Food processing and fortification were considered.	Not included. The analysis is limited to estimates of food and dietary nutrient supplies for each country, which can be considered a lower bound for prevention of deficiency.
GND (2018) [55]	Estimates national nutrient availability by combining FAO food balance sheet (amount of food) and USDA food composition database (amount of nutrients in different foods).	None beyond those already accounted for in the units (i.e., folate and vitamin A)
EAT-Lancet (2019) [9]	Proposed ranges of healthy food intakes are possible to produce within planetary boundaries.	Iron and zinc, though dietary reference groups and corresponding justification for phytate content were not adequately justified (iron) or incorrect for the context (zinc) [57].
DELTA model (2021) [56]	Estimates regional nutrient adequacy under 2 global population scenarios by combining FAO food balance sheets (amount of food) and USDA food composition database (amount of nutrients in foods).	Protein and essential amino acids are adjusted according to digestibility. Zinc and iron are adjusted according to vegetarian and vegan dietary patterns at the total diet level only, and not for contributing foods.

Abbreviations: EFSA, European Food Safety Authority; EU, European Union; GENuS, Global Expanded Nutrient Supply; GND, Global Nutrient Database; NASEM, National Academies of Sciences, Engineering, and Medicine; NNR, Nordic Nutrition Recommendations; IFPRI-IMPACT, International Food Policy Research Institute - International Model for Policy Analysis of Agricultural Commodities and Trade.

not all bioavailability differences that may affect dietary outcomes (Table 1) [9,49–56].

At the same time, nutrient supply studies rarely account for the influence of bioavailability on nutrients, and risk miscalculating nutrient supplies across populations with diverse dietary patterns (Table 1). Across the 5 major studies highlighted in Table 1, nutrient bioavailability was assessed for protein, indispensable amino acids, vitamin A, folate, zinc, and iron, though not all 6 nutrients in any single study. In the 2019 EAT-Lancet Commission report on healthy and sustainable diets, which recommends a large shift from ASFs to PSFs to preserve planetary health, nutrient bioavailability was considered for zinc and iron. However, the fixed bioavailability concentrations chosen for iron were not reported, and those chosen for zinc were likely too high given the high phytate consumed in the reference diet (~2400 mg). The report did not consider the WHO- and EFSA-recommended bioavailability concentrations across different dietary scenarios (e.g., vegetarian or vegan) [9,57], thereby failing to adequately acknowledge the complexity that bioavailability introduces and its importance to the outcomes of the report.

Beal et al. [57] provide an example in their recalculation of the 2019 EAT-Lancet Planetary Health Diet. Compared with nutrient reference values, they estimate iron and zinc bioavailability at 10% and 26%, respectively, and adjust the EAT-Lancet diet accordingly. For vitamin A, however, they acknowledge that bioavailability is already accounted for in the nutrient recommendation and therefore should not be adjusted for in the model. The 2025 EAT-Lancet Commission [58] is a commendable extension of sustainable dietary recommendations that account for only food system transformations, yet its consistent recommendation of a Planetary Health Diet with low caloric contributions from ASFs (13% of calories in the Planetary Health Diet are recommended from ASFs) may not ensure nutrient adequacy for vulnerable populations, particularly without robust bioavailability considerations. Recent work has also highlighted potential concerns about micronutrient inadequacy in sustainable diets [59].

Current Best Practices

Given growing concerns about the bidirectional relationships between environmental change and diets, a core objective of recent food systems research has been to evaluate and propose population-level dietary changes while understanding the contributions of constituent food groups. A recent review of the Mediterranean Diet and its potential contribution to biodiversity preservation as a sustainable, healthy diet is one such example [60]. To accurately calculate and assess nutrient supplies and dietary patterns, incoming food systems research should follow existing best practices to account for nutrient bioavailability, particularly for iron and zinc, 2 nutrients for which deficiencies are common among populations with low intake of ASFs [61]. For nutrients that do not account for bioavailability in the requirement metric itself, as is the case for vitamin A [47], the ideal solution would be to incorporate models that account for major factors that inhibit or enable absorption. However, this level of granularity in accounting for bioavailability is not possible for most nutrients due to insufficient quantitative data on foods and nutrients [14]. In its absence, researchers should use their own context-specific dietary reference values or, if unavailable, harmonized global dietary reference values, such as those proposed by Allen et al. [48], and select the appropriate bioavailability concentration for iron (5%, 10%, or 16%) and zinc (26%, 30%, 35%, or 44%). These values are based on WHO and the National Academies of Sciences, Engineering, and Medicine estimates of iron intake that account for ASF intake, high ascorbic acid-containing foods, and unrefined phytate-rich grains and legumes [14,49]. Alternatively, if accounting for bioavailability at the food-group level, one hybrid approach has been to assign individual food groups a phytate concentration using 1 of the 3 iron concentrations or 4 zinc concentrations, depending on heme and phytate content, respectively [62]. Although imperfect, even accounting for bioavailability differences in iron and zinc alone would go a long way toward enabling studies such as the EAT-Lancet Commission to accurately model (and thus propose) nutritionally adequate diets across both HIC and LMIC settings.

For nearly all the 27 nutrients examined in this perspective, bioavailability is higher in ASFs than in PSFs. Although a dietary shift in high ASF-consuming contexts toward more nutritionally balanced plant-based diets can reduce the environmental footprint and improve protection against noncommunicable diseases [63], such a transformation would have implications for bioavailability and corresponding nutrient intake recommendations. In low ASF-consuming contexts, such as many LMICs, bioavailability considerations are particularly important given the high burden of nutrient deficiencies and related undernutrition. Even in HICs with higher average ASF consumption, micronutrient deficiencies can be a concern for certain populations, underscoring the need to consider bioavailability across multiple contexts [64]. When proposing dietary changes, we need to carefully consider the implications of bioavailability and use the best available, context-specific bioavailability evidence to model nutritionally adequate diets.

Future Research Needs

Many interacting elements can affect a nutrient's bioavailability, and we do not suggest undertaking an exhaustive exploration of each permutation of nutrient interaction. However, the effective use of well-designed isotopic human tracer studies may provide a clear avenue to bridge this data gap by following the fate of nutrients consumed through digestion, metabolism, and excretion [28]. More broadly, we advocate for a systematic approach to account for bioavailability across the research spectrum. In nutrition science, this means prioritizing the adoption of a standardized approach to accurately measure bioavailability across a sufficient range of foods and nutrients to address the overwhelming lack of bioavailability data. For cohort-based research, this necessitates awareness of the complexity of bioavailability and the enrollment of diverse, representative cohorts to understand the multitude of pathways by which nutrient intake may be altered prior to nutrient absorption. For applied food systems research, this necessitates incorporating best practices to account for bioavailability and basing decisions on total dietary intake of appropriate context-specific factors, such as phytate intake.

The implications of inadequate bioavailability accounting do not end in food systems research but also extend to food technology, nutrition equity, food policy, and their interdisciplinary intersections. In the food technology sector, the importance of developing climate-smart plant-based meat alternatives must be considered in terms of the nutrient gaps of the target audience. For nutrition equity, advocates for a global shift from ASFs to PSFs for the sake of environmental health must consider the nutrient gaps these recommendations may create and the importance of bioavailability in food-insecure settings, especially in subsistence settings where ASF consumption is often lowest [65]. At the policy level, decisions on trade and agricultural subsidies – especially in food-insecure settings – must consider evolving region-specific dietary needs and the nutritional implications of reliance on staple foods. The nature of food systems research necessitates collaboration among experts across disciplinary lines to codevelop new expertise that captures the coordinating and sometimes competing interests within the planetary health realm. At the same time, these interdisciplinary collaborations must incorporate nutrition scientists with expertise in understanding the complex factors that influence absorption and accounting for these when possible. Nutrition scientists with a thorough understanding of food composition tables and nutrient databases may also play a crucial role in reducing the frequency of methodological pitfalls in such interdisciplinary research, such as ignoring or inadequately accounting for bioavailability.

To increase PSF consumption in high ASF-consuming countries, we must accurately account for changes in bioavailability to develop strategic dietary guidelines [57]. Similarly, if we intend to evaluate and propose food system interventions in regions dependent on unrefined grains and legumes, we must ensure that the nutrient reference values on which we base our recommendations account for factors that affect bioavailability, such as dietary phytate content, lest we risk perpetuating longstanding health concerns. To build a food systems landscape where sustainability, healthfulness, and supply concerns dictate context-specific dietary recommendations for ASF and PSF consumption, greater recognition must be given to the significant impact that bioavailability can have on estimates of the nutritional value of individual foods and food groups, as well as on the nutrient adequacy of overall diets, helping to shape a more environmentally sustainable and socially equitable food system for generations to come.

Author contributions

The authors' responsibilities were as follows – CDG, MT: designed the research; KMN, AT, JZ-M, HE, VÖ: conducted the research; KMN, AT: compiled and synthesized the data; all authors wrote the paper; KMN: had the primary responsibility for the final content; and all authors: read and approved the final manuscript.

Conflict of interest

CDG is an Editorial Board Member for the *American Journal of Clinical Nutrition*, but played no role in the Journal's evaluation of the manuscript. All other authors report no conflicts of interest.

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