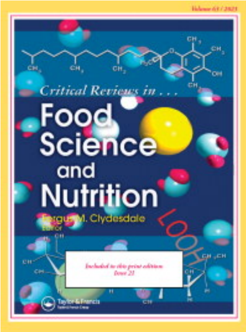

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REVIEW

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The role of holistic nutritional properties of diets in the assessment of food system and dietary sustainability

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ABSTRACT

Advancing sustainable diets for nutrition security and sustainable development necessitates clear nutrition metrics for measuring nutritional quality of diets. Food composition, nutrient requirements, and dietary intake are among the most common nutrition metrics used in the current assessment of sustainable diets. Broadly, most studies in the area classify animal-source foods (ASF) as having a substantially higher environmental footprint in comparison to plant-source foods (PSF). As a result, much of the current dietary advice promulgates diets containing higher proportions of PSF. However, this generalization is misleading since most of these studies do not distinguish between the gross and bioavailable nutrient fractions in mixed human diets. The bioavailability of essential nutrients including β-carotene, vitamin B-12, iron, zinc, calcium, and indispensable amino acids varies greatly across different diets. The failure to consider bioavailability in sustainability measurements undermines the complementary role that ASF play in achieving nutrition security in vulnerable populations. This article critically reviews the scientific evidence on the holistic nutritional quality of diets and identifies methodological problems that exist in the way the nutritional quality of diets is measured. Finally, we discuss the importance of developing nutrient bioavailability as a requisite nutrition metric to contextualize the environmental impacts of different diets.

KEYWORDS
Bioavailability; healthy diets; sustainable nutrition; food biodiversity; dietary guidelines; nutrient quality

Introduction

Food is at the core of human and planetary health. Our diets are a reflection of our food systems (Fanzo et al. 2020b) and vice versa, with both elements forming an active feedback mechanism. Nutritionally robust dietary patterns are patterns of food intake beneficial to health that also help prevent malnutrition and chronic diseases (WHO 2020). They are characterized by adequate intake of whole grains, millets, vegetables, fruits, nuts, seeds, healthy fats, legumes, and/or dairy, poultry, fish, but limited intake of ultra-processed foods and beverages (UPFB) and processed red meat (Afshin et al. 2019; Hu 2002; Schulze et al. 2018). Such dietary patterns arising from diversified agro-ecosystems have been found to have a lower environmental footprint and are also known to encourage ecological resilience (Frison 2016; Smith et al. 2020). On the other hand, unhealthy dietary patterns and/or excessive consumption of foods with a greater environmental footprint are key drivers of climate change (Willett et al. 2019).

The present-day food systems are reported to result in up to 7 trillion USD in environmental costs and 11 trillion USD in costs to human life (FOLU 2019; UNFSS 2021). The dysfunctional global food system is a dichotomy of record food production in recent years (Holt-Giménez et al. 2012) versus a leading cause of rising malnutrition. Globally, one in nine people is hungry/undernourished, and one in three people is overweight/obese and susceptible to/suffering from micronutrient deficiencies (GNR 2020). Since 2014, an additional 60 million people have been impacted by hunger, and preliminary estimates predict that the COVID-19 pandemic may result in a further 83–132 million people being undernourished (FAO-IFAD-UNICEF-WFP and WHO 2020; GNR 2020).

Further, extensively-processed foods dominate dietary landscapes in high-income, and increasingly in the middle- and low-income countries forming up to 50% of the total purchased calories. As a result, the current dietary landscape puts over 33% of the global population at serious risk of diet-related non-communicable diseases (NCDs) (FAO-IFAD-UNICEF-WFP and WHO 2018; GNR 2020). It is estimated that risks arising from poor dietary patterns have resulted in 11 million deaths and 255 million disability-adjusted life-years in 2017 (Afshin et al. 2019). Further, over 3 billion

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people including over 50% of the population living in Southern Asia and sub-Saharan Africa cannot afford diverse, healthy diets, and over 1.5 billion people worldwide cannot afford a diet that fulfills basic nutrient requirements (FAO-IFAD-UNICEF-WFP and WHO 2020).

Many studies have investigated the nutritional adequacy and environmental sustainability of different food systems (Béné et al. 2019; Clark et al. 2019; Fanzo and Davis 2019; Gustafson et al. 2016; Jones et al. 2016) in terms of specific foods or nutrients. However, malnutrition is not merely the lack of sufficient quantities of food (Swaminathan 2012) or a single nutrient because nutrition is a function of dietary patterns (Moughan 2020). Similarly, sustainable diets are not merely the consumption or not of certain food groups but realistic, geographically representative, socio-culturally acceptable diets that can help fulfill population nutrient requirements at the least possible environmental cost (Johnston, Fanzo, and Cogill 2014a). Therefore, a comprehensive approach that can consider the holistic properties of foods in relation to food system sustainability is required. For this review, holistic nutritional properties of dietary patterns include nutrient bioavailability, dietary biodiversity, food structure, and beneficial properties of bioactive food compounds (Lachat et al. 2018; Moughan 2020).

This article (1) overviews the nutrition metrics used in the current analysis of sustainable diets; (2) summarizes the significance of dietary biodiversity, a whole-diet approach and food structure; (3) outlines the importance of nutrient bioavailability; and (4) identifies future steps in assessing and achieving healthy sustainable diets.

Sustainable diets and food systems: knowledge to date

This review addresses the following research questions: What is the general set of nutritional properties of diets used in the present assessment of (a) food system sustainability, (b) dietary sustainability, and (c) the ability of common diet types in the prevention of malnutrition and risk of chronic diseases? How well do these nutritional properties encapsulate the true nutritional value of diets? Which further nutritional properties should be included to strengthen the current analysis of sustainable food systems? A comprehensive list of related search terms and keywords were derived based on the research questions. The complete list of keywords is provided in the supplemental material. Briefly, the following key search terms were used: ("diet" OR "dietary pattern" OR "nutrition" OR "food-based dietary guidelines" OR "healthy reference diet" OR "recommended diet" OR "animal source foods" OR "flexitarian" OR "alternative sources of protein" OR "plant-based diets") AND ("bioavailability" OR "essential nutrients" OR "indispensable amino acids" OR "dietary diversity" OR "food properties" OR "digestibility" OR "NCDs" OR "malnutrition" OR "nutrition security") AND ("sustainable diets" OR "sustainability" OR "nutrient production" OR "environmental footprint" OR "biodiversity" OR environmental impact of food per unit digestible/bioavailable (fraction of) essential nutrient/s) AND ("food system" OR "food strategies" OR "score" OR "global assessment" OR "diet optimisation") AND/OR ("modelling" OR "metrics" OR "score" OR "global assessment" OR "diet optimisation").

Searches were conducted during June 2020–June 2021 using various databases including Scopus®, Web of Science™, PubMed® and Google Scholar. The publications on diet/food system modeling and nutrient production were restricted to key studies published between 2014 and 2021. However, no time restrictions were placed on studies that helped identify nutritional attributes of diets that can combat malnutrition and reduce the incidence of chronic diseases. Relevant studies were exported to EndNote X9 citation management software (Clarivate Analytics), and the full-text of the selected studies were reviewed. Characteristics of interest were tabulated for descriptive, qualitative review, and all the relevant evidence and elements significant to sustainable nutrition were synthesized to address the objectives of the review. The key focus and outcome of this study were to highlight specific physiological/nutritional properties of diets that can enhance food system sustainability.

Modeling studies and reviews

Sustainability of diets is determined by an extensive range of agricultural, health, sociocultural, environmental and socioeconomic factors (FAO 2012; Johnston, Fanzo, and Cogill 2014b). Recent assessments of sustainability also include a suite of nutrition metrics (Ahmed, Downs, and Fanzo 2019; Chaudhary, Gustafson, and Mathys 2018; Eme et al. 2019). Diet models with relatively low environmental impact, for example, traditional Mediterranean Diet (Donini et al. 2016) or territorial diets constructed based on regional food traditions, for example, the New Nordic Diet (Hachem, Vanham, and Moreno 2020) may also be used in sustainability analyses of other diets (Grosso 2018; Meltzer et al. 2019). Different modeling approaches that capture the intrinsic properties of food systems are also utilized in estimating the sustainability of different diets (Gustafson et al. 2016; Willett et al. 2019). Some of the key modeling studies that assess the sustainability of diets are outlined in Supplementary Table 1. These studies utilized: (a) food supply data from the FAO food balance sheets (FBS), standard national-level supply data, health/nutrition survey data or data from empirical studies that determine the dietary intake of foods/food groups, (b) dose-dependent meta-analysis and disability-adjusted life-years for understanding health impacts, (c) life-cycle assessments for environmental impacts, and (d) diet optimization approach by linear or non-linear programming to model data in retrospect (Chaudhary, Gustafson, and Mathys 2018; Chaudhary and Krishna 2019; Chen, Chaudhary, and Mathys 2019; Clark et al. 2019; Costa Leite et al. 2020; Ridoutt et al. 2019). The dietary scenarios that are modeled and evaluated are based on: (a) commonly known dietary types such as vegan, vegetarian, lacto-ovo-vegetarian and omnivorous, or involve the construction of either a single healthy reference diet or dietary patterns based on stated national food-based dietary guidelines (FBDGs), (b)

Table 1. The myriad of factors that influence the digestion and bioavailability of key nutrients.

Factor	Nutrients affected[1]	Organic or inorganic compounds (including nutrients) involved in inhibition (↓) or enhancement (↑) of nutrient absorption	Proposed mechanism
Speciation, that is, chemical form of the nutrient	Vitamin B-6, niacin, folate, iron, zinc, selenium (↓/↑)		Isomeric form, organic or inorganic form, heme- or non-heme are digested and absorbed differently
Food structure	Carbohydrates, dietary fiber, proteins (including indispensable amino acids), fats, vitamin A, β-carotene, other carotenoids, vitamin B-12, folates (↓/↑)		Bioaccessibility/nutrient location within the tissue (insoluble matrix and cellular structure; bound nutrients; microstructure of processed foods; nutrient + phytochemical complexes; nutrients covalently bond to macromolecules) Effect on accessibility to catalytic site for enzymatic digestion Milk protein micelle, microstructure and macrostructure, and meat macrostructure influence digestion kinetics, absorption of indispensable amino acids
Noncompetitive interactions between nutrients and organic components in diets	↓ Carbohydrate (starch), protein, fats, thiamin, vitamin C, fat-soluble vitamins (including carotenoids), folate, iron, zinc, calcium, magnesium, copper (dietary and endogenous), selenium, chromium	↓ Phytate (*myo*-inositol hexaphosphate plus magnesium, calcium, or potassium phytate), polyphenols, oxalic acid, dietary fiber, protein ↑ Organic acids (citric, lactic, acetic, butyric, propionic, formic acids), vitamin C, protein, fat	Hydrophobic interaction, covalent bond formation, the formation of toxic compounds
Competitive interactions between two or more inorganic nutrients	↓ Iron, zinc, copper	↓ Excess zinc intake, iron, folate, calcium,	Inhibition of absorption
Food processing, preparation, fermentation, food additives	↓ Carbohydrate (starch), Basic indispensable amino acids (including lysine, arginine, methionine), thiamin, riboflavin, vitamin C, water-soluble vitamins (leaching) ↑ Carbohydrate (starch), protein digestibility, niacin, biotin iron, zinc, calcium, iodine		Thermal exposure-induced Maillard reaction, oxidation of sulfur-containing amino acids, isomerization or neoformation of amino acids, protein aggregation, loss of heat-labile micronutrients, lipolysis lower bioavailability Thermal exposure-induced inactivation of antinutritional factors (protease inhibitors, avidin, lectin (agglutinins), goitrogens, α-amylase inhibitors, thiaminases) enhances bioavailability Boiling (reducing oxalate content) enhances bioavailability Cooking methods/food processing unit operations impact digestibility, digestive kinetics and metabolic utilization of nutrients
Luminal and mucosal factors	Vitamin A, β-carotene, vitamin B-12, folate, iron, zinc, calcium, copper (↓/↑)		Atrophic gastritis (associated hypochlorhydria and *Helicobacter pylori* infection) hinders the bioavailability of micronutrients dependent on pH levels by impairment of vitamin release from complexes, deconjugation and absorption Reduced gastric acid secretion lowers solubilization of inorganic nutrients and reduces gastric pepsin activity influencing protein hydrolysis, also causing malabsorption of vitamin B-12 Reduced transit time in the gut due to infection may affect nutrient absorption Structural alteration of intestinal/gut mucosa affects nutrient homeostasis and intestinal and brush border membrane enzyme activity Nutrient homeostasis, endogenous nutrient secretion influence nutrient uptake from the diet
Systemic factors	Vitamin B-12, vitamin B-6, thiamin, vitamin D, calcium, magnesium, iron, zinc, copper, chromium (↓/↑)		Age, sex, ethnicity, genotype, physiological state (e.g. pregnancy), nutrient status of the host, co-existing gut disorders or chronic and acute infections impact digestion and absorption
Gut microbiota	Fractional energy absorption, carbohydrates, short-chain fatty acids, the overall process of nutrient absorption (↓/↑)		Bacterial overgrowth/dysbiosis in the upper gut can disturb the integrity of intestinal mucosa, increase intestinal/gut permeability and lower nutrient absorption Bacterial overgrowth also linked to atrophic gastritis
Geographical location, soil quality, potable water quality (Food contaminants via the food supply)	Trace minerals (↓/↑)	↓ Heavy metal toxicity	Antagonistic interactions between contaminants and micronutrients lead to reduced absorption Inhibiting constituents in soil lower the bioavailability of nutrients Optimal soil composition can be a source of absorbable nutrients (e.g. Calcareous soils as a source of absorbable calcium)
Environmental pollutants	↓ Iron, zinc, copper, selenium, chromium	↓ Cadmium, lead, zinc, mercury	Antagonistic reactions lead to lowered absorption Pollutants may lead to gut dysbiosis and consequent nutrient malabsorption

[1]Note: Data collated from various sources (Åberg et al. 2020; Bharatraj and Yathapu 2018; Fardet et al. 2019; Gibson 2007; Gibson, Perlas, and Hotz 2006; Goswami et al. 2017; Huang et al. 2020; Jumpertz et al. 2011; Marze 2017; Reynolds et al. 2019; van den Berg, van der Gaag, and Hendriks 2002a; van den Berg, van der Gaag, and Hendriks 2002b; WHO and FAO 2004; Wortsman et al. 2000).

↓ Indicates a reduction in bioavailability (applies to all nutrients succeeding this sign); ↑ Indicates enhancement of bioavailability (applies to all nutrients succeeding this sign); ↓/↑ Indicates a factor's ability to reduce or enhance the bioavailability of a said nutrient (applies to all nutrients succeeding this sign).

diets with a reduced intake of environmentally damaging foods/food groups, (c) substitution of meat (particularly red and processed red meat) with plant foods/dairy/eggs/chicken/cultured meat, and (d) diets with reduced consumer food waste and loss (Kim et al. 2019; Rosi et al. 2017; Wood, Alam, and Dupras 2019).

We reviewed the nutrition metrics used in 23 studies in the area of dietary/food system sustainability published since 2017 (see Supplementary Table 1). Twelve of the 23 reviewed studies have considered individual nutrients in their analysis but not all of the studies have included all of the essential micronutrients and indispensable amino acids (Supplementary Table 1). Each of the studies uses a different set of nutrition metrics to analyze the nutrient adequacy of commonly consumed diets or modeled dietary scenarios. Several studies have evaluated the nutritional quality of diets based on the concept of "restriction" (Springmann et al. 2018). For example, dietary risk and/or changes to environmental impact have been estimated by restricting an ingredient or nutrient (e.g. limiting sugar/saturated fat intake), restriction of a food group (e.g. limiting red meat or dairy intake) and/or restriction of total intake (e.g. limiting or replacing meat/dairy foods) (Kim et al. 2019; Springmann et al. 2018).

Only four of the 23 studies include some form of bioavailability data in evaluating the nutritional value of the studied diets and food systems. Further, the bioavailability of only a few nutrients such as iron, zinc, β-carotene, and/or dietary protein was considered. Besides, protein bioavailability is generally evaluated using the protein-digestibility corrected amino acid score (PDCAAS) that does not provide a true picture of dietary protein quality (discussed in detail in a subsequent section). Only one single study considered the effect of food matrix on dietary quality and nutrient uptake (Magkos et al. 2019), thus highlighting our current limited understanding of the effect of holistic properties on dietary sustainability.

As in the case of nutrition metrics, not all studies consider all environmental metrics. In general, the effect of diets on the earth system is examined through the ecological parameters of greenhouse gas (GHG) emissions, land use, water use, nitrogen application, phosphorus application, biodiversity loss, dietary diversity, and energy input. Only one study reviewed data on energy and protein per unit area of agricultural land, and energy and protein conversion efficiency (Alexander et al. 2017). This shows the lack of data around the environmental impact of food production in relation to the bioavailable nutrient fraction in different foods.

In the published literature on sustainability assessments of food systems and diets, the following host of metrics allow for the most comprehensive assessment of nutritional quality: (a) dietary diversity and nutrient adequacy ratios, (b) nutrient bioavailability, (c) diet-related morbidity/mortality (dietary risk), (d) dietary equity, (e) intake of processed foods, (f) holistic diets (healthy dietary patterns suited to personal, cultural, and traditional preferences), (g) nutrient density of foods, (h) food affordability and availability, (i) sociocultural aspects of diets, (j) energy and protein conversion efficiency, (k) recommended nutrient requirements, and (l) food-based dietary guidelines (Ahmed, Downs, and Fanzo 2019; Eme et al. 2019; Fanzo and Davis 2019; Springmann et al. 2018). However, to date, few sustainability studies (Supplementary Table 1) have undertaken a comprehensive analysis of the nutritional quality of different diets (Ahmed, Downs, and Fanzo 2019; Barre et al. 2018; Eme et al. 2019; Magkos et al. 2019), and no study included all of the above metrics in the analysis of the diet-environment link. The recently published Food Systems Dashboard documents an extensive range of nutrition metrics (Fanzo et al. 2020a, 2020b) but does not directly address nutrient bioavailability. Some recent studies have also acknowledged that the current modeling of environmental and nutritional attributes of different foods does not consider food properties including food structure and bioactive compounds (Jochems et al. 2020; Lucas et al. 2021). It is of note that as new models are developed, some of these factors such as the bioavailability of priority nutrients important for global nutrition security are now being considered (Barnsley et al. 2021; Smith et al. 2021). In summary, the reviewed studies indicated a lack of consensus on nutrition metrics for evaluating the nutritional quality of foods/diets. However, most modeling studies, thus far, advocate increasing the consumption of plant-source foods (PSF) and limiting the consumption of animal-source foods (ASF), including meat and dairy products, and in particular red meat for both better health and environmental outcomes.

The state of nutrient supply

Several authors have investigated the national or global state of food supply and/or nutrient adequacy in relation to the tripartite forms of malnutrition of under-nutrition, micronutrient deficiencies and over-weight/obesity (Scrinis 2020) or in the context of established nutrition guidelines. These studies examined: (a) nutrient production at the commodity level, (b) food availability and dietary intake, (c) current and predicted (based on climate change) production of major agricultural commodities, and/or (d) nutrient supply and adequacy at the population level (Beal et al. 2017; Geyik, Hadjikakou, and Bryan 2020; Herrero et al. 2017; Siegel et al. 2014; M. R. Smith et al. 2016). These estimates are primarily based on food supply data from FAO or country-level (food/nutrient) production along with established levels of nutrient requirements in human nutrition (Beal et al. 2017; Springmann et al. 2016). Supplementary Table 2 provides a summary of eight key studies conducted from 2014 to 2020 in the area of food situation worldwide.

At present, in over half of the countries worldwide, cereals are the largest supplier of energy, protein, iron and zinc (Geyik, Hadjikakou, and Bryan 2020). Globally, small and medium farms (≤20 ha and 50 ha, respectively) grow 51–77% of the volume of cereals, fruits, pulses, roots and tubers, and vegetables, thereby supplying 51–77% of essential nutrients including protein, vitamins A and riboflavin, calcium, zinc except for iron, and folate (Herrero et al. 2017). The nutritional yield of vitamin A and B-12 is low in several world regions, including parts of China, India, Europe, the

Table 2. Digestible indispensable amino acid score (DIAAS) and protein digestibility-corrected amino acid score (PDCAAS) for common foods and concentrated/isolated dietary protein foods/supplements and mixed meals.

	Digestible indispensable amino acid scores (DIAAS)[1,2]		Protein digestibility–corrected amino acid score (PDCAAS)[1,3]
Food	Young children (6 months to 3 yr)	Older children, adolescents, and adults	Older children, adolescents, and adults
Cereal grains and breakfast cereals			
Corn, yellow dent, raw		48	
Wheat, raw	45	54	51
Wheat, whole, cooked	20		
Rice, polished, cooked	37		
Brown rice, cooked	42		
Minor cereal/Millet			
Oats, rolled, cooked	54		
Proso millet, cooked	7		
Sorghum, raw		29	
Rye		48	59
Barley		47	59
Buckwheat	68		
Foxtail millet	10		
Corn-based breakfast cereal	1	1	8
Legumes and pulses/Plant-based protein concentrate/isolate			
Kidney beans, cooked	77	59-88	65
Peas, cooked	57	58-68	
Moong beans	68	86	
Chickpeas	67	76	
Adzuki beans	59	64	
Broad beans	53	60	
Soy flour		89	98
Soy protein isolate		84	93
Pea protein concentrate		62	75
Rice protein concentrate		37	42
Oat protein concentrate		67	69
Nuts and oilseeds			
Peanuts, roasted		43	51
Pistachio, raw		86	73
Pistachio, roasted		83	81
Meat, fish and poultry			
Beef, raw		97	
Beef, boiled		99	
Beef, roasted		91	
Pork		114	100
Tilapia		100	
Chicken breast		108	100
Dairy and eggs			
Cow milk, whole milk		116	100
Sheep milk		109	
Goat milk		124	
Whole milk powder	122	143	
Milk protein concentrate	118	120	100
Skimmed milk protein		105	100
Whey protein concentrate	97	107	100
Whey protein isolate	109	100	99
casein		109	100
Whole egg, boiled		113	100
Protein complementation (mixed meals)			
Milk to breakfast cereal (60:40)	107		
Cereals, millets, legumes, and egg-based complementary foods for young children aged 18–24 mo	80		
Cereals, millets, legumes, and egg-based complementary foods for young children aged 18–24 mo + 200 g milk	101		
Cereals, millets, legumes, and egg-based complementary foods for young children aged 18–24 mo + 50 g whole egg	100		

[1]Values derived from (Bailey, Carughi, and Stein 2020; Bailey and Stein 2019; Burd et al. 2019; FAO 2013a; Han et al. 2019; Han et al. 2020; Mathai, Liu, and Stein 2017; Phillips 2017; Rutherfurd, Fanning, et al. 2015; Shivakumar et al. 2019). All values selected from studies estimating or documenting the true ileal digestibility of essential amino acids and proteins from different dietary sources in humans, or growing pigs, or in growing rats.

[2]The DIAAS value is the lowest digestible indispensable amino acid reference ratio using the amino acid requirement pattern of either young children and/or older children, adolescents, and adults. Values for DIAAS are calculated from the ileal digestibility of amino acids.

[3]Values for PDCAAS were calculated from the total tract digestibility of crude protein.

North American Great Plains, Southern Brazil, Northern Argentina, East African highlands, and parts of West Africa since the major sources of these essential sources are limited to roots and tubers for vitamin A precursors, and meat and fish for vitamin B-12 (Herrero et al. 2017). While the diversity of agricultural production is greater in Europe, Africa, Asia and the western part of South America, it is poor in many parts of Australia, North America and South America

(Herrero et al. 2017). Except for South Asia and sub-Saharan Africa, globally, national daily energy availability per capita has been continually increasing since 1961 (Beal et al. 2017). However, the current micronutrient density of the global food supply is unable to fulfill population requirements of calcium, iron, vitamin A, folate, zinc, riboflavin, and vitamin B-12 (Beal et al. 2017; Geyik, Hadjikakou, and Bryan 2020). Currently, 93% of countries do not have adequate vegetable supply to meet the FAO/WHO recommended daily intakes of 240–300 g/d (Kalmpourtzidou, Eilander, and Talsma 2020). Based on the agricultural sector data, the supply of fruits and vegetables in low- and upper-middle-income countries falls short by 58% and 13%, respectively, and this shortage is likely to increase to 70% by 2025 in the former countries (Siegel et al. 2014). Reduced fruit and vegetable consumption-associated micronutrient deficiency and negative health effects are predicted to be the leading risk factor for climate-related mortality by 2050 in Southeast Asia and the Western Pacific regions (Springmann et al. 2016). O'Hearn et al. (2019) report that Latin American regions appeared to have healthier patterns in comparison to Asia and Sub-Saharan Africa and this trend may be attributable to the lower supply of protein and certain micronutrients in the latter regions.

Critical limitations of current models: a nutritional perspective

Food availability

The existing models investigating the sustainability of food systems use FAO's FBS data (FAO 2020a) as direct input (Smith et al. 2016). The FBS provides data on "the per capita supply of each food item available for human consumption" (FAO 2020a). The actual amounts of food consumed may be lower due to food waste at the retail level and losses of edible portions of food and nutrients at the household level (FAO 2020b). Also, FBS calculates nutrient quantities of raw commodity and not edible portions (Macdiarmid et al. 2018) and does not report the individual amount of each of the items used to estimate the nutrient content of a given commodity group.

For example, the commodity group "Milk – excluding butter" encompasses dairy products like milk, cheese and yoghurt or other regional variants and the commodity group "Fruits, other" includes apricots, mangoes and plums, and so on, each with distinct nutrient composition that are also likely to be purchased and consumed in different amounts across households (Macdiarmid et al. 2018; Smith et al. 2016). Not surprisingly, Del Gobbo et al. (2015) have shown that the FAO food-supply estimates from individual-based national surveys can overestimate the actual dietary intakes of vegetables and whole grains by up to 75–270%, respectively, or underestimate the dietary intake of legumes and nuts and seeds by up to 50–29%, respectively. To overcome these limitations, some authors (Beal et al. 2017; Macdiarmid et al. 2018; Smith et al. 2016) have proposed a weighted or disaggregated approach to obtain more accurate estimates of per capita food/nutrient supply. However, most modeling studies do not ascertain the actual contribution of individual food sources to nutrient intake.

Food biodiversity and composition

The significant variations in the nutritive value of foods stemming from food biodiversity are largely overlooked in food systems modeling. The commonly used, standard food composition tables (FCTs), and food composition databases (FCDBs) (Charrondiere et al. 2013) are not representative of biodiversity-related nutrient- and non-nutrient variations or variations occurring due to genetics, growing conditions, feed, soil, climate, season, storage, and processing (FAO 2017). The composition of the same food can be vastly different across countries and regions within a country. Thus, using a singular FCDB for global estimates or carrying out inter-FCBD comparisons can result in under- or over-estimation of the nutrient content of foods (Burlingame, Charrondiere, and Mouille 2009; Charrondiere et al. 2013; Stadlmayr et al. 2011). For example, the protein content of rice can vary from 5 to 14.6 g/100 g edible portion (raw), while the β-carotene content of sweet potato, mango and banana can vary between 100–23,100, 20–4320 and <1–8500 mcg/100 g edible portion (raw), respectively (Burlingame, Charrondiere, and Mouille 2009). Therefore, the use of regional/national FCDBs is important but not always followed in modeling. Also, food composition data is the quantity of nutrients present in foods (i.e. before they are processed and cooked), and hence do not indicate the actual bioavailable fraction of a nutrient in a given food item. Furthermore, resource-poor settings, extensive heterogeneity of supply and wider rural-urban distribution gaps complicate the estimation of true nutrient availability from FCDB.

Loss of food biodiversity

Serious loss of the genetic diversity of cultivated crops and genetically related wild plant species and domesticated breeds of animals have increased the susceptibility of agricultural systems to pests, pathogens, climate change, and endangered nutrition security. The global food system is also threatened by insufficient support for indigenous peoples' food systems that promote food biodiversity (IPBES 2019).

Plant foods make up nearly 80% of our global diets (Angelico and Villani 2020; Hunter et al. 2020). Continual investment toward high-yielding starchy staples has incentivized monoculture farming and disincentivized nutrition- and climate-sensitive, resilient and higher-aggregate-yield polyculture systems (Bioversity International 2017; HLPE 2019). Of the 5000–70,000 edible plant species (Bioversity International 2017), maize, rice, wheat, soybean, and palm oil (and sugar) collectively contribute to the highest global intake of calories, protein and fat (Herforth, Johns, et al. 2019) with the three cereal grains alone accounting for >50% of global plant food-derived energy intake (Bioversity

International 2017). Additionally, over 550 (of the total 6790) domesticated breeds of mammals used for food and agriculture had become extinct by 2016, with nearly 1000 more breeds likely to be threatened (IPBES 2019). As a result, human diets are converging toward a homogeneous global standard diet (Herforth, Johns, et al. 2019). Dietary diversity from neglected and underutilized plant and animal species can mean the difference between population nutrient sufficiency or insufficiency (Burlingame, Charrondiere, and Mouille 2009; FAO 2010, 2012). Greater food biodiversity has also been found to have a significant positive correlation with the overall quality of diet (Dwivedi et al. 2017; Penafiel et al. 2019). Agrobiodiversity, therefore, can play a substantial role in enhancing nutrition security, sustainability and equity, and ecosystem services and functions (Thrupp 2000).

Disproportionate nutritional and environmental consequences of ultra-processed foods

Most foods for human consumption are processed to some extent. Hence, there is a need to distinguish between foods that are processed minimally and extensively-altered UPFB. Minimally processed foods are natural foods that are altered to a limited extent by certain industrial or household processes to either remove inedible part(s) or extend their shelf-life, for example, pasteurized milk, dehusked wholegrains, wholegrain flour, and frozen vegetables (Monteiro et al. 2018). On the other hand, UPFB are industrial formulations that are created using highly refined ingredients that are either extracted from foods and/or derived from food compounds. UPFB contain relatively higher amounts of sugar, salt and oils and fats, and may also contain numerous food additives which contribute to making the formulation hyperpalatable (Monteiro et al. 2018). Examples of UPFB include carbonated drinks, packaged foods like biscuits, cakes, breakfast cereals, instant foods such as soups and noodles, milk formulas, reconstituted meat products, and plant-based meat analogues (Baker et al. 2021; Monteiro et al. 2019; Monteiro et al. 2018). Dietary patterns with significant, habitual consumption of UPFB pose a significant public health risk (Kelly and Jacoby 2018; Lustig 2020; Stuckler and Nestle 2012; Swinburn et al. 2019) and have been implicated in diabetes (Popkin 2015), dyslipidemia (Rauber et al. 2015), risk of cardiovascular and cerebrovascular diseases (Srour et al. 2019), and cancer (Fiolet et al. 2018). Excessive consumption of UPFB is also found to be a major contributor to the global syndemic of malnutrition and climate crisis (Swinburn et al. 2019).

UPFB are associated with intensive agriculture/livestock and require a greater amount of resources to manufacture owing to either the use of several specialized ingredients and energy-intensive processing (Fardet and Rock 2020). The nutrient composition-relative transport footprint of UPFB is also potentially high (Tasca, Nessi, and Rigamonti 2017; Wood, Alam, and Dupras 2019). However, both the true environmental impact of UPFB and their actual intake in national and global diets are not fully understood (Del Gobbo et al. 2015; Fanzo et al. 2020a; FAO 2020a). Nevertheless, recent studies have found that reduced consumption of UPFB may help lower diet-related GHG emissions (da Silva et al. 2020; Niles et al. 2018).

Single nutrient or food versus a holistic view of dietary patterns

The amounts, proportions, variety and combinations of different foods and beverages in a diet, and their habitual frequency of consumption (USDA 2014) gives rise to a dietary pattern that has: (i) a complex profile of different essential and non-essential nutrients which have non-additive, interactive, synergistic and intercorrelated effects on the individual's nutritional status (Hoffmann 2003; Hu 2002; Moughan 2020), and (ii) many non-nutrient food compounds that are known to have significant physiological effects beyond nutrition (Moughan 2020), for example, the primary role of dietary proteins in human nutrition is delivering essential amino acids for protein synthesis and energy, however, during their digestion dietary proteins may also release bioactive peptides that are beneficial to health (Moughan et al. 2014) Healthy dietary patterns can positively modulate both the physiology and function of the host (Badimon, Mendieta, and Vilahur 2015) and the gut microbiota (Bear et al. 2020) and help prevent the occurrence and severity of diet-related NCDs and communicable diseases (Branca et al. 2019; Myles 2014; Olatona et al. 2018). In contrast, unhealthy dietary patterns (alongside a sedentary lifestyle) may be involved in the pathogenesis of chronic diseases (Struijk et al. 2014), cognitive decline (Jacka et al. 2015; Shakersain et al. 2016) and increased susceptibility to infectious diseases (Butler and Barrientos 2020). Poor dietary patterns may also lead to a loss in the diversity of gut microbiota, especially of colonic microbes that ferment dietary fiber (Dreher 2018; Heinritz et al. 2016; Segata 2015; Wu et al. 2011). Dietary nutrients and bioactive compounds can also act as epigenetic factors (Milagro et al. 2013), leading to germline inheritance of diet-related NCDs (Huypens et al. 2016), and chronic undernutrition can result in an intergenerational cycle of malnutrition (Yehuda et al. 2016). The importance of nutrition in the prevention and management of malnutrition and diet-related NCDs such as type 2 diabetes and obesity have been reviewed extensively (Branca et al. 2019; Budreviciute et al. 2020; Forouhi et al. 2018; Keats et al. 2021; Scott et al. 2020) and hence have not been discussed here.

Current nutrition metrics categorize individual nutrients and foods into broad groups based on their effect on health. The nutrients are "qualified" as essential to health, for example, vitamin A, calcium and protein or "disqualified" as detrimental to health, for example, saturated fats, cholesterol, or sugar. However, such categorization does not accurately measure the true nutritional contribution of a given dietary pattern (Drouin-Chartier et al. 2020; Krauss and Kris-Etherton 2020). Further, dietary scenarios that are predicted based on the theoretical availability and not bioavailability of essential nutrients (Barre et al. 2018; Chaudhary and Krishna 2019; Chen, Chaudhary, and Mathys 2019;

Herrero et al. 2017; Rosi et al. 2017; Smith et al. 2016; White and Hall 2017)) are limited in their ability to determine the nutritional potential of different diets. In particular, the use of calorie sufficiency-driven nutrition metrics cannot address the problem of chronic hunger, severe undernutrition and hidden hunger in low- and middle-income countries (LMIC) and food insecure populations elsewhere. Therefore, nutrition metrics for modeling ecological impacts of diets must be based on a whole-diet approach and should consider nutrient bioavailability of diets rather than taking a dietary approach that emphasizes what nutrients/foods to avoid (Drewnowski, Amanquah, and Gavin-Smith 2021; Drewnowski and Fulgoni 2014).

Some studies classify dietary patterns into “prudent” (intake of unprocessed grains, fruit, vegetables, lean meat, and fish) or “Western” (intake of UPFB, fast foods and processed red meats). The Western dietary pattern results in a higher intake of total sugars and fats and sodium, alcohol and *trans* fatty acids, and a lower intake of dietary fiber, folate, and omega-3 fatty acids (Hu 2002). While such classification of diets is beneficial in ascertaining nutritional quality, it must be noted that there is no single prudent dietary pattern. Diets from different regional agricultural scenarios suitable to diverse economic, cultural, and social contexts can be healthy and sustainable. Notably, traditional diets of indigenous peoples originating from biodiverse food systems are nutritionally superior to most modern-day diets. A range of geographically-appropriate cultivars or landraces of various grains, millets, fruits, vegetables, and a variety of (ASF) including milk and milk products and fermented foods, have been the cornerstone of traditional/territorial diets (FAO 2013b; Shondelmyer et al. 2018; Tamang et al. 2020). Finally, healthy diets do not always have a lower or neutral carbon footprint. Both healthy and unhealthy diets can be either high or low GHG emitting depending on the constituent foods (Macdiarmid 2013). It is recognized that increases in GHG emissions will be necessary for some countries to achieve nutrient sufficiency (FAO-IFAD-UNICEF-WFP and WHO 2020).

The following parts of this article describe the importance of holistic nutritional properties of diets in greater detail.

Digestibility and bioavailability of nutrients

For the purpose of this review, for all nutrients except proteins, digestibility refers to the breakdown of foods into the potentially accessible matter by the physical and chemical processes of digestion in the gut lumen (Carbonell-Capella et al. 2014). Further, the fraction of the digested nutrient that is available for absorption refers to the bioaccessibility of the nutrient (Parada and Aguilera 2007). On the other hand, bioavailability is defined as the fraction of a bioaccessible nutrient (or bioactive compound) that can reach the systemic circulation and is therefore available for metabolic and physiological processes and tissue distribution (Fairweather-Tait 1993; Galanakis 2017; Hambidge 2010; Parada and Aguilera 2007; Srinivasan 2001). It is the bioavailability of nutrients and bioactive compounds that determines their bioactivity at physiological levels of intake. Therefore, bioavailability is the fundamental indicator of the quality of nutrients supplied by any dietary pattern or food system. However, in case of dietary protein, amino acid digestibility refers to “the proportion of consumed amino acids that is absorbed” (FAO 2013a).

The digestion, uptake and utilization of dietary nutrients are influenced by three distinct yet interdependent factors, specifically diet-related, host-related, and environmental factors (Gibson 2007). First, the chemical form of a nutrient, noncompetitive interactions between nutrients and other organic compounds, competitive interactions between two or more inorganic nutrients, food preparation methods, food processing unit operations, and the inherent food structure or matrix can all determine digestibility and nutrient uptake of foods (Gibson 2007; Singh and Gallier 2014). Second, host-related factors including age, gender, gut factors/diseases, smoking, genetic variations, and nutritional status also influence nutrient uptake (Bohn et al. 2017). Host-related intestinal and luminal factors are of critical importance in nutrient bioavailability. For example, gut disorder/diseases such as atrophic gastritis and environmental enteric dysfunction cause gastric acid hyposecretion (El-Omar et al. 1997) and increased permeability of intestinal epithelial barrier (Faubion et al. 2016), respectively, resulting in reduced absorption of key nutrients (Kaptan et al. 2000; Kelly 2021). Further, in both healthy and malnourished individuals, the gut microbiome may also affect nutrient absorption and metabolism. Briefly, gut microbiota plays a role in intestinal epithelial cell proliferation and maturation, health of the mucosal immune system and regulation of host genes responsible for nutrient uptake thereby modulating nutrient absorption and the nutritional status of the host (Kane, Dinh, and Ward 2015b). Gut bacteria modulate energy metabolism and production of short-chain fatty acids and niacin, pantothenic acid, vitamin B-6, vitamin B-12, biotin, folate, vitamin K, and can enhance absorption of minerals including iron (Heiss and Olofsson 2018; Kane, Dinh, and Ward 2015b; Kau et al. 2011). Host-related factors and gut microbiome introduce significant intra-/interindividual variability in nutrient bioavailability (Bohn et al. 2017). Third, environmental contaminants such as cadmium and lead in the food supply can lead to reduced bioavailability of iron, zinc, and calcium (Gibson 2007). Further, environmental pollutants-induced disturbances in the quantity, quality, or diversity of gut commensal flora (dysbiosis) may result in nutrient malabsorption (Forgie et al. 2020; Kane, Dinh, and Ward 2015a; Kordas, Lönnerdal, and Stoltzfus 2007).

The bioavailability of macro- and micronutrients from different food matrices and across broad dietary patterns have been the subject of previous reviews (FAO 2013a; Gibson 2007; Gibson, Perlas, and Hotz 2006; Platel and Srinivasan 2016; Singh and Gallier 2014). The key factors affecting nutrient bioavailability and the complex regulation of nutrient bioavailability in humans have been summarized in Table 1. Table 2 presents the DIAAS and PDCAAS values for some common single foods and a few examples of protein complementation in a few common mixed meals (discussed in detail in the next section). Table 3 the known potential bioavailability (i.e. estimated bioavailability of individual nutrients from mixed human meals containing differing amounts of promoters and inhibitors known to affect nutrient absorption) of micronutrients across different common diet types. While it appears that the bioavailability of most of the micronutrients is similar across different diets, the bioavailability of some essential nutrients such as β-carotene, vitamin B-12, iron, and zinc varies significantly and is especially lower in foods commonly consumed as a part of vegetarian and vegan diets. Further, the bioavailability of minerals such as calcium is dependent on not just the estimated percentage of fractional absorption but also on the calcium content of the food ingested. For example, while it appears that the fractional (intestinal) absorption of calcium is greater from broccoli (61%) than from dairy foods (32%), when adjusted for the calcium content in these foods, broccoli would provide only 22 mg of calcium/serving (71 g) while milk and yoghurt can provide up to 96 mg of calcium/serving (240 g) (Weaver, Proulx, and Heaney 1999). Similarly, although the bioavailability of food folates across diet types is around 50%, numerous factors are known to influence folate bioavailability. Boiling of folate-rich green vegetables and legumes can destroy folate by 50–80% and 50%, respectively (Dang, Arcot, and Shrestha 2000; McKillop et al. 2002). Further, the digestibility of folate from plant cellular structure may be incomplete and the presence of organic acids may negatively impact folate absorption (Sanderson et al. 2003). On the other hand, dietary constituents like certain proteins and ascorbic acid can enhance folate absorption (Sanderson et al. 2003).

Despite the importance of nutrient bioavailability in achieving nutrition security, there remains a paucity of evidence on nutrient uptake from different food matrices and dietary patterns. However, the existing data shows that ASF contain bioavailable forms of vitamin A, vitamin B-12, iron, and zinc, while PSF are a significant contributor to vitamin C, several B vitamins, vitamin E, dietary fiber, and important bioactives including phytochemicals. In particular, for facilitating a smooth transition towards dietary patterns with higher PSF, there is a need to increase awareness about the dietary significance of minimum intakes of certain staple ASFs. For example, complete omission of dairy and intake of unfortified plant-based milk alternatives alone can put populations at risk of iodine deficiency (Dineva, Rayman, and Bath 2021). Further, while vegan diets were associated with a better cardiovascular health, they were also linked to an increased risk of Vitamin B-12 and iron deficiencies

Table 3. The potential bioavailability of select essential vitamins and minerals across different diet types, including vegan, vegetarian, non-vegetarian diets and Western-type diet.

Nutrient, Dietary (unless otherwise stated)	Potential nutrient bioavailability from common diet type (%)*[1]		
	Non-vegetarian	Lacto-ovo vegetarian	Vegan
Vitamin A (Pre-formed)	90	–	–
Pro-vitamin A carotenoids (at dietary fat intake of 10–40 g)[2]	3–65	3–65	3–65
Pro-vitamin A carotenoids (without co-ingestion of adequate dietary fat)	5–10	5–10	5–10
Riboflavin	60–95	60–95	60–95
Pantothenate (food-bound pantothenic acid)	40–61	40–61	40–61
Vitamin B-6	75	75	75
Vitamin B-12[3]	4–65	4–50	Risk of vitamin B-12 deficiency (fermented foods, yeast-containing foods or fortified foods may be a source of cobalamin in vegan diets)
Vitamin C	70–90	70–90	70–90
Folate (Naturally occurring food folates)	50	50	50
Synthetic folate	85–100	85–100	85–100
Niacin[4]	30–69	30–69	30–69
Vitamin K	5	5	5
Iron	12–18	5–10	5
Zinc	15–50	15–30	15–27
Iodine	> 95	> 90	> 90
Selenium[5]	20–90	20–90	20–90
Calcium[6]	8–30	8–30	8–30
Copper	50–75	50–75	50–75
Magnesium	40–50	40–50	40–50
Molybdenum	75	75	75
Phosphorus	55–70	55–70	55–70

*Potential bioavailability refers to estimated bioavailability of individual nutrients from mixed human meals containing differing amounts of promoters and inhibitors known to affect nutrient absorption.
[1]Data derived from (Doets et al. 2013; Haskell 2012; Hunt 2003; Melse-Boonstra 2020; Perignon et al. 2018; Platel and Srinivasan 2016; Roth-Maier et al. 2000; van Het Hof et al. 2000; Watanabe 2007; Weaver, Proulx, and Heaney 1999; WHO and FAO 2004, Institute of Medicine (US) Panel on Micronutrients 2001; EFSA 2015).
[2]β-carotene absorption spinach = ~5–26%; carrots = ~7–65%; broccoli = 12%.
[3]Fish = 42%; sheep = 56–89%; chicken = 61–66%; eggs ≤ 9%; milk and milk products = 65%.
[4]Unfortified cereal grains = 30%; Other foods = 50–69%.
[5]Wheat = 80%; brazil nuts and beef kidney = 90%; tuna = 20-60%; other foods = 80%.
[6]Fractional (intestinal) absorption values; dairy and fortified foods = 30%; green leafy vegetables/Brassicaceae/roots and tubers/other vegetables = 8–61%; beans = 22–27%.

and lower bone mineral content in children aged 5–10 y (Desmond et al. 2021). Also, lowered intake of ASF might prevent children from attaining optimal height (Desmond et al. 2021). While acknowledging the planetary health benefits of shifting to dietary patterns with increased consumption of PSF, we must also recognize the critical role of ASF in the improvement of pregnancy outcomes and cognitive and physical development in young children and prevention of biochemical and functional nutritional deficiencies, stunting and wasting (Alonso, Dominguez-Salas, and Grace 2019; Dror and Allen 2011). ASF effectively supplement diets of food insecure populations that survive on starchy staples and help reduce morbidity from illness (Neumann, Harris, and Rogers 2002; Smith et al. 2013). Livestock also provides income security for small-holder farmers and positively influence the nutritional status of these vulnerable populations (Randolph et al. 2007). Furthermore, affordable nutrition is key to nutrition security. ASF such as eggs and milk and milk products have been shown to be among the lowest-cost sources of protein along with legumes (Drewnowski 2010). Dairy foods may be the lowest-cost source of calcium (apart from providing significant amounts of retinol, vitamin D, riboflavin, pantothenic acid, cobalamin, vitamin B-12, and phosphorus) (Graulet 2014) for consumers from different socioeconomic backgrounds, while fruits and vegetables are the lowest-cost sources of vitamin C (Drewnowski 2010).

Notably, nutrient bioavailability data in conjunction with a previously proposed hybrid nutrient profiling approach that takes nutrient density, food groups, and dietary ingredients into account (Drewnowski et al. 2019) and low-burden metrics to measure diet quality (Herforth et al. 2020) can be a feasible holistic approach to estimating the environmental footprint of food patterns in relation to their true nutritional adequacy.

Importantly, dietary patterns with inadequate utilizable protein intakes are also associated with inadequate intakes of essential micronutrients (FAO and WFP 2020; O'Hearn et al. 2019; Rao et al. 2001) in both acute food insecurity hotspots and affluent world regions alike. The section below describes the importance of protein quality in sustainable diets.

Protein quality of diets

Dietary protein will be crucial for global food and nutrition security (Drewnowski, Amanquah, and Gavin-Smith 2021). LMIC and certain demographics in most countries are reported to be at risk of protein deficiency (Moughan 2021). In the limited dietary studies that include (dietary protein) bioavailability as a nutrition metric, PDCAAS values have been used to describe the protein quality of foods. However, PDCAAS has several drawbacks (Rutherfurd, Fanning, et al. 2015) and the UNFAO recommends DIAAS for estimating dietary protein quality (FAO 2013a). It is of note that, unlike PDCAAS, DIAAS allows for the determination of digestibility of each individual amino acid and can also help estimate a protein source's ability to improve the amino acid balance of other poorer-quality protein sources, that is, it helps understand the benefits of protein complementation and protein quality of mixed diets (Rutherfurd, Fanning, et al. 2015).

As shown in Table 2, animal source foods including milk and meat have generally greater DIAAS values than plant food sources and PDCAAS may overestimate or underestimate the protein quality of foods. However, protein complementation of relatively low value DIAAS foods with high quality animal proteins can substantially improve the protein quality of diets. For example, Shivakumar et al. (2019) used the dual-isotope tracer method to determine the true ileal digestibility of indispensable amino acids in commonly consumed complementary foods for Indian children aged 1–3 y. The authors found that the DIAAS value of the tested complementary diets was 80% but could be improved to DIAAS values of 101% or 100% if 200 g milk or 50 g egg, respectively were included in their daily diet (Shivakumar et al. 2019). Therefore, DIAAS can be used as a potential tool to efficiently utilize dietary protein across populations with different habitual diets (Moughan 2021). Moughan (2021) reported that when the average daily gross protein intakes were corrected for true ileal protein digestibility, the average adult daily protein intake fell short for most of the 103 countries that were evaluated. The study also found that in the case of mixed diets containing both animal and plant source proteins, the diet should contain >40% protein from ASF to fulfill protein requirements. This analysis would have significant implications for groups with increased protein requirements including young children, adolescents, pregnant and breastfeeding women, children suffering from protein-calorie malnutrition, people suffering from certain diseases and for athletes.

With respect to specific indispensable amino acids, in a majority of the countries where cereals are the major source of dietary protein, the average per person lysine intake is found to be approaching the limit of lysine deficit, suggesting that global lysine supply will be a critical factor in achieving protein security (Leinonen et al. 2019). Therefore, while it is important to moderate the intake of ASF, drastic reductions in the intake of ASF in world regions suited to sustainable livestock production would deprive populations of quality protein and micronutrient-dense foods (Wolfe et al. 2018).

DIAAS values can also be useful for the quantitative comparison of the environmental impacts of different foods and dietary patterns. The land and freshwater use, GHG emissions, global warming potential, and biodiversity loss associated with production of animal and plant protein sources should be corrected for digestible protein fraction/supply of the respective sources. For example, Loveday (2019) applied DIAAS values to a previous study on the environmental footprint of various foodstuffs by Poore and Nemecek (2018) that compared protein-rich foods on an per 100 g protein basis, that is, on the quantitative basis alone. (Poore and Nemecek 2018). Loveday (2019) noted that when GHG emissions are adjusted for protein quality using DIAAS values, the environmental impact of peanuts increased by 130%, and that of bovine milk decreased by 24%. These findings of Loveday (2019) are consistent with Moughan (2021) who noted that when environmental effects are corrected for digestible protein/amino acid, the carbon footprint of ASF may be lower than current estimates that are based on gross protein alone. For example, when GHG emissions are expressed per unit digestible lysine, ASF such as eggs, fish, poultry and pork had lower GHG emissions per unit digestible lysine than that of PSF such as grains and soymilk (Moughan 2021). Further, given that lysine is reported to be the first limiting indispensable amino acid across different dietary patterns, it would be important to determine the digestible lysine content of foods and mixed diets.

Food structures and bioavailability of nutrients

Food structure affects both the extent and process of the oral, gastric and intestinal digestion of a food, which impacts the digestibility and bioaccessibility of nutrients held within the structure (Dickinson 2014; Golding 2019). Food structure can also regulate postprandial events and satiation (Dickinson 2014). However, limited research has been conducted about the role of structural attributes of foods in achieving nutrient adequacy.

Natural food microstructure is defined as either the spatial arrangement of the cells and the intercellular space in food material and their interactions, or the organization of several similar/dissimilar elements, their binding into a unit and the interrelationship between the individual elements and their groups (Aguilera 2005; Golding 2019; Karim et al. 2018; Moughan 2020). These structures range from a nanometer scale at the molecular level for various nutrients and phytochemicals to a centimeter-scale at the tissue level (Moughan 2020). A well-known example of how food structure impacts the delivery and bioavailability of nutrients is the micellar structure of casein proteins in milk. Casein protein is highly phosphorylated and forms nano-clusters of calcium and phosphate that enable the delivery of relatively high concentrations of calcium and phosphate (Holt et al. 2013).

Table 4 summarizes the current knowledge about the role of food structures in the digestion and absorption of carbohydrates, proteins, and fats, and the respective complex mechanisms of action. Despite lack of systematic studies in the area, it is becoming increasingly evident that native food structure, or the fractionation of original raw foods and food matrix destructuring during cooking or manufacturing of UPFBs may have a significant impact on nutrient uptake (Fardet 2015; Fardet and Rock 2020; Moughan 2020; Parada and Aguilera 2007; Reynolds 1988).

Synergistic and cumulative action of bioactive compounds and nutrients

Food-derived bioactive compounds are "extra-nutritional" constituents that can modulate physiological or cellular activities resulting in health benefits (Kitts 1994; Kris-Etherton et al. 2004). Dietary bioactives are extensively metabolized by the gut mucosa and microbiota and by the liver xenobiotic Phase 1 and 2 enzymes (Cassidy and Minihane 2017), and these (bio)transformations result in the activation and/or absorption of the bioactives (Alldritt et al. 2019; Carmody and Turnbaugh 2014; Spanogiannopoulos et al. 2016). Bioactive components can be multifunctional, and have many health benefits: ACE-I inhibition, anti-inflammatory, antioxidant, vasodilatory, cognitive functioning, anticancer, regulation of digestive enzyme activity, hypoglycemic, hypolipidaemic, antibacterial, hepatoprotective, modulation of flows of endogenous gut protein, and epigenetic modification (Kris-Etherton et al. 2002; Moughan et al. 2014; Shashirekha, Mallikarjuna, and Rajarathnam 2015).

At least 25,000 phytochemicals and other bioactive have been identified from PSF and ASF (Heber and Bowerman 2001; Minkiewicz et al. 2008). A vast majority of bioactive molecules from PSF and ASF remain unknown. Dietary research investigating the cumulative effects of food synergy and dietary patterns is nascent (Jacobs and Steffen 2003). Nevertheless, dietary patterns with bioactive compound-rich foods have been shown to lower the risk of several chronic diseases including coronary heart disease, type 2 diabetes mellitus and obesity and certain types of cancers (Ortega 2006; Shashirekha, Mallikarjuna, and Rajarathnam 2015; Shondelmyer et al. 2018; Wirfält, Drake, and Wallström 2013). Notably, dietary supplements may help alleviate severe- and moderate acute nutrient deficiencies arising from chronic malnutrition, medical conditions and/or suboptimal diets from ineffective food systems. However, there is inconclusive evidence regarding the use of dietary supplements in healthy individuals (Rautiainen et al. 2016). Thus, a balanced healthy diet is considered to be the best approach to ensure optimal intake of all essential nutrients (Rautiainen et al. 2016). Healthy diets supply essential nutrients through a complex food matrix. The inherent synergy of micro- and macronutrients within this matrix is the dietary pattern that appears to provide optimal satiety and nutrient assimilation. The rate of absorption of nutrients from meals and the gut anabolic response to meals is likely to be different to that for specific nutrients. For example, co-ingestion of the antihypertensive lactotripeptides in a protein matrix has been shown to prolong their portal bioavailability (Ten Have et al. 2015).

Research priorities and future developments

The Food and Agriculture Organization defines sustainable diets as nutritionally adequate, safe, healthy, culturally acceptable, economically affordable diets that have a low environmental impact (FAO 2012). However, thus far, the nutrient quality of such diets has not been adequately defined. A multipronged approach is required to achieve global nutrition security, and this includes a better understanding of the nutritional quality of sustainable diets. Given the significance of holistic properties of diets, we propose the following key nutrition-centric research priorities and/or steps for both assessing and achieving sustainable diets.

Table 4. Recent findings of the effect of food structure on the breakdown, processing, and bioavailability of macronutrients in the gut.

Macronutrient	Structural factors	Effect on the digestive process or digestive tract	Proposed mechanism[1]
Carbohydrate starch (principal carbohydrate in plant seeds and tubers)	Extracellular structures of the plant, porosity and specific interfacial area Molecular packing of amylopectin and amylose molecules	Rate of hydrolysis ↑/↓	Surface pores on native granules may allow penetration of water and amylase to the core of the granules
	Native starch	Rate of digestion ↓	Lowered gelatinization or remain ungelatinized
	Structural changes from heating and cooking of native starches	Rate of digestion ↑	Cooking with water gelatinizes starch
	Higher amylose content	Starch digestion ↓	Reduced hydrolysis
	Increased amount of resistant starch (recrystallized amylose)	May escape digestion in the small intestine	Resistant to enzymatic hydrolysis
	Presence of a protein network around starch granules	Rate of digestion ↓	Gelatinization and retrogradation of starch affected Slows down the digestion of starch by a-amylase in the gut
	Soluble dietary fiber	Rate of glucose release ↓	Increased viscosity and/or delayed gastric emptying
	Lipids within the starch structure	Starch hydrolysis ↓	Starch-lipid complexation
Protein	Presence of antinutritional factors (phytic acid, phenolic compounds, enzyme inhibitors, saponins, lectins and hemagglutinin) in plant foods with substantial protein (legumes and cereals)	Protein digestibility ↓ Indispensible amino acids ↓ Trypsin inhibitors cause ↑ satietogenic hormone cholecystokinin Lectin and hemagglutinin can damage intestinal mucosa (besides agglutinating erythrocytes) α-amylase, α-glucosidase, lipase inhibition (Mineral absorption ↓, can impair overall digestion, can cause toxicity and health disorders if ingested in high concentrations/plant foods not properly cooked/processed)	Inhibit the activity of digestive proteases and peptidases (amylase, trypsin, chymotrypsin and lipase), and glucosidases (by blocking the active site of the enzymes) Negatively charged phytic acid binds to positively charged minerals lowering mineral absorptivity Formation of reversible and irreversible tannin-protein complexes Lectin and hemagglutinin (glycoproteins) reduce transport and hydrolytic functions of the enterocyte and may upregulate the function and metabolism of the whole gut Increased cholecystokinin reduces food intake and body weight α-amylase, α-glucosidase, lipase inhibition may prevent diabetes mellitus and obesity
	Native molecular structures of proteins	Susceptibility to hydrolysis ↑/↓	Differing tertiary conformations and regions with different affinities for hydrophobic and hydrophilic environments
	Soluble proteins	Gastric emptying ↑ Digestion carried out by pancreatic enzymes	Due to greater solubilization
	Disordered proteins, for example, caseins (Caseins are loose and highly flexible structure; assembled into a supramolecular structure called micelle)	Rapid hydrolysis Relatively greater degree of gastric digestibility Ileal digestibility 94 % Gastric emptying ↓	Casein conjugates to form a gastric coagulum due to the dual action of stomach acid and proteases Greater exposure of preferential sites for proteolysis Slower postprandial release of amino acids
	Highly folded, compact conformations, for example, β-lactoglobulin (Proteins with globular, well-defined three-dimensional structure)	Limited digestion in the stomach Ileal digestibility 97–98 %	Resistant to enzymatic hydrolysis Whey proteins cause a rapid release of amino acids into plasma
	Presence of fiber and other polysaccharides	Digestibility of proteins ↓ Bioavailability of proteins ↓	Increase in viscosity of gut contents prevent access of digestive enzymes to proteins Electrostatic interactions prevent access to cleavage sites on protein/ peptides
	Presence of phytochemicals	Bioavailability of proteins ↓	Binding with proteins
	Protein hydrolysates made up of short-chain peptides, soy proteins, gluten	Satiety ↑	Induce release of cholecystokinin in the gut
	Primary, secondary, or tertiary structures of lactalbumin, gelatin, casein, soy protein isolate or beef muscle	Basal endogenous ileal amino acids in the gut ↑/↓ Modify release of amino acids and bioactive peptides across the stomach and small intestine	Influence gut metabolism and nitrogen losses

(*Continued*)

Table 4. (*Continued*)

Macronutrient	Structural factors	Effect on the digestive process or digestive tract	Proposed mechanism[1]
	Structural changes from milling, soaking, germination, autoclave and microwave treatment and fermentation	Improved digestion of plant foods with substantial protein	Reduce the effects of antinutritional factors
	Structural changes from heating, cooking, emulsification Maillard reaction	Rate of hydrolysis ↑/↓ via enhanced or limited peptidic digestion Amino acid bioavailability ↓	Proteins denatured/aggregated, change molecular flexibility/unfold resulting in higher accessibility Protein-sugar crosslinking may result in loss of bioavailability of some key amino acids, for example, lysine (which may, in turn, lower absorption and conservation of calcium)
	Structural changes due to food processing (depending upon temperature, pH, ionic strength, and shear, denaturation) – lead to the formation of fibrils, micro-particles, spherical micro-gels, and fractal gel aggregates	Rate and extent of protein digestibility ↑/↓	Heterogenous, complex structures alter the accessibility of protein molecules to gut proteases and peptidases
Fats (Triacylglycerols, phospholipids and cholesterol)	Fats from natural food (meat, dairy, nuts)/triacylglycerols coated with solubilizing layer/multilayer of membrane phospholipids and proteins, cell walls	Rate and extent of fat digestion ↑/↓ Bioaccessibility of lipids ↑/↓	Modulation of binding of lipase to the oil-water interface (Small molecule surfactants, phospholipids, and proteins differently impact lipase action) Susceptibility to digestive enzyme activity Susceptibility to microbial fermentation
	Extracted plant/animal fats in processed foods (yoghurt, cheese, spreads, imitation creams, salad dressings, gravies, sauces, ice-creams, confectionery products, chocolate) are largely incorporated in the form of an emulsion	Rate and extent of fat digestion ↑/↓ Bioaccessibility of lipids ↑/↓	Modulation of binding of lipase to the oil-water interface (Small molecule surfactants, phospholipids, and proteins differently impact lipase action) Susceptibility to digestive enzyme activity Susceptibility to microbial fermentation
	Resulting surface area of the interface, the nature of the emulsifier or the stereospecificity of native dietary triacylglycerol molecules, droplet size of fat emulsion, composition, charge, thickness, and rheology	Rate and extent of fat digestion ↑/↓ Bioaccessibility of lipids ↑/↓	Modulation of binding of lipase to the oil-water interface (Small molecule surfactants, phospholipids, and proteins differently impact lipase action) Susceptibility to digestive enzyme activity Susceptibility to microbial fermentation
	Interesterification and hydrogenation	Rate of fat digestion ↑/↓ Bioaccessibility and absorption of certain fatty acids	
	Emulsification	Fatty acid absorption ↑ Lipid β-oxidation ↑	
	Acid-stable emulsion	Gastric emptying rate ↓	
	Emulsion with the smaller lipid droplets	Extent of digestion ↑	Higher rate of lipolysis

[1]Data derived from (Åberg et al. 2020; Alfieri et al. 2017; Dave et al. 2016; Dupont and Tomé 2020; Golding 2019; Mackie and Macierzanka 2010; Muir and O'Dea 1993; Parada and Aguilera 2007; Rutherfurd, Cui, et al. 2015; Samtiya, Aluko, and Dhewa 2020; Singh and Gallier 2014; Stanstrup et al. 2014; Thilakarathna et al. 2016).

↓ Indicates reduction in digestibility and/or bioavailability (applies to all nutrients succeeding this sign); ↑ Indicates enhancement of digestibility and/or bioavailability (applies to all nutrients succeeding this sign); ↓/↑ Indicates a factor's ability to reduce or enhance digestibility and/or bioavailability (applies to all nutrients succeeding this sign)

Building future food systems that deliver consistent bioavailable nutrient supply

Despite current efforts, the world is off-track to achieve the United Nations Sustainable Development Goal (SDG) targets 2.1 (nutrition security for all) and 2.2 (eradication of malnutrition). Up to 27 countries are heading toward a COVID-19-driven nutrition crisis (FAO-IFAD-UNICEF-WFP and WHO 2020). Furthermore, given that rising atmospheric CO_2 is projected to reduce nutrient (including protein, iron, zinc, thiamin, riboflavin, pantothenic acid, and folate) concentration in staple crops such as rice (Zhu et al. 2018), nutrient bioavailability will be a critical concern. This article shows that assessing the sustainability of diets without considering the bioavailable nutrient quality of diets might contribute to poor dietary choices resulting in increased incidence of malnutrition and diet-related chronic diseases. Therefore, food production-related land use, freshwater use, and associated impacts on biodiversity and soil quality should be estimated in relation to bioavailable/digestible nutrient contribution of foods. Soil health, in particular, soil organic matter and biodiversity, are crucial for crop nutrient uptake, which influences both crop yield and nutritional value of the crop (Wall, Nielsen, and Six 2015). Thus, soil security is crucial for food security (McBratney, Field, and Koch 2014) and for meeting the global nutritional requirement of essential minerals, including calcium, magnesium, iron, zinc, selenium, and other nutritionally important trace elements (Oliver and Gregory 2015).

Research focus on dietary contributions of neglected and underutilized crops

Further evidence is needed on the nutrient bioavailability/digestibility in climate-resilient neglected and underutilized local crops including millets, pulses, fruits, and vegetables. This will enable the measurement of dietary sustainability in relation to the nutritional contribution of these future foods (Li and Siddique 2020). Also, in future studies, it would be important to determine dietary species richness (a count of the number of different species consumed per day) since it is a highly useful tool for measuring both sustainability and nutritional quality of diets (Lachat et al. 2018).

Preservation and revival of traditional dietary patterns

From a public health nutrition perspective, what is most urgently needed is a whole-diet approach to better understand the nutrition-health-environment nexus. While no singular diet type can ensure nutritional adequacy for all, regionalized approaches may prove to be effective in achieving nutrition security. Prudent dietary patterns (characterized by more frequent intakes of whole grains, vegetables, fruits, nuts, seeds, legumes and/or dairy, poultry, fish, and healthy fats) and local traditional diets may help achieve greater adequacy of dietary fiber, limiting amino acids, micronutrients and phytochemicals (FAO 2009, 2012). Traditional diets have been described as a cultural heritage of millennia of exchange of people. They are based on a variety of diversified local traditional foods that are closely linked to a given geographical location, for example, Mediterranean diet, traditional Indian diet, diets of the Pacific Small Island Developing Countries, and diets of indigenous populations worldwide (Burlingame and Dernini 2011; FAO 2009; Shondelmyer et al. 2018; Vogliano et al. 2021). Therefore, in implementing sustainable diets, FBDGs should help preserve and underscore the importance of the diverse range of low environmental impact dietary patterns existing within a region and community (Johns and Eyzaguirre 2006; Ridoutt, Hendrie, and Noakes 2017).

Reconceptualizing FBDGs

FBDGs may need to be re-conceptualized to include detailed information on both nutrient bioavailability and bioactive compounds (Heber and Bowerman 2001) of dietary patterns and regionally available biodiverse foods in relation to their relative environmental impact. FBDGs that are better tailored to individual populations can be used as a practical tool for choice architecture and nudge strategy to adopt biodiverse, sustainable diets (Ensaff 2021; Herforth, Arimond, et al. 2019).

Conclusions

Overall, while most of the relevant findings in the study of dietary sustainability are diverse and the discipline itself is in its nascent stages, this review shows that there is significant evidence for making sustainable food systems nutrition-centric. We acknowledge that the evidence presented herein may be subject to publication bias in that studies were extracted only from published literature, and the selected primary studies relevant to the modeling of food sustainability utilized mixed methods. Future work would entail scoping data from non-mainstream scientific publications to source country- and region-specific nutrition data and predicted food system scenarios.

All forms of malnutrition, including stunting, wasting, underweight, micronutrient deficiencies and overnutrition, remain a staggering global nutritional problem (GNR 2020). Vitamin A, Vitamin B-12, iron, zinc, calcium, and lysine deficiencies are widespread, and the burden of diet-related NCDs is rising. Thus, the nutrition component of sustainable diets needs to be given due consideration. Characterization of the environmental impacts of diets is highly challenging. However, using reductionistic nutrition metrics such as food composition alone can result in poor dietary choices and outcomes. Bioavailability is a critical determining factor of the true nutritional value of a diet and its potential health effects. Nutrition metrics must, therefore, also include measures of bioavailable/digestible nutrient fraction and nutrient density. Such comprehensive nutrition metrics offer a feasible approach to distinguish between bioavailable nutrient-rich dietary patterns (with minimal UPFB intake) and energy-dense, lower nutrient quality diets. This would help inform better choices for healthy and sustainable eating. Future work is required to develop consensus-based methodologies for estimating the digestibility and bioavailability of essential nutrients from different diets. Much work is also required to determine the bioavailability of nutrients from different food matrices. Finally, more information on the holistic nutritional properties of sustainable diets in FBDGs would encourage the adoption of healthy sustainable diets.

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