Perspective: Striking a balance between planetary and human health: Is there a path forward?

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Sources of support: All authors contributed to, read, and approved the final manuscript. Editorial assistance was provided by Jackie Read PhD of Chill Pill Media Ltd. and funded by Danone Institute International (a non-profit organization).
**Abbreviations:** BMD, bone mineral density; BMI, body mass index; GHGE, greenhouse gas emissions; HCP, healthcare professional; HIC, high-income country; LCA, lifecycle assessment; LIC, low-income country; LMIC, low-to-middle income country; MMT, million metric tons; NCD, non-communicable disease; RNI, reference nutrient intake; SFA, saturated fatty acids; SGA, small for gestational age; TDD, territorial diversified diets; WFN, Worldwide Fund for Nature; WHO, World Health Organization; WRI, World Resources Institute

**Abstract**

The global adoption of predominantly plant-based sustainable healthy diets will help reduce the risk of obesity- and malnutrition-related non-communicable diseases while protecting the future health of our planet. This review examines the benefits and limitations of different types of plant-based diets in terms of health and nutrition, affordability and accessibility, cultural (ethical and religious) acceptability, and the environment (i.e. the four pillars underlying sustainable healthy diets). Results suggest that, without professional supervision, traditional plant-based diets (vegan, vegetarian and pescatarian diets) can increase the risk of nutritional deficiencies among infants, children/adolescents, adult females, pregnant/lactating women and the elderly. In contrast, flexitarian diets and territorial diversified diets (TDDs, e.g., Mediterranean and New Nordic diets) that include large quantities of plant-sourced foods, low levels of red meat and moderate amounts of poultry, fish, eggs and dairy can meet the energy and nutrition needs of different populations without the need for dietary education or supplementation. Compared to vegan, vegetarian and pescatarian diets, more diverse flexitarian diets and TDDs are associated with reduced volumes of food waste and may be more acceptable and easier to maintain for people who previously followed western diets. Although flexitarian diets and TDDs have a greater impact on the environment than vegan, vegetarian and pescatarian diets, the negative effects are considerably reduced compared to western diets, especially if diets include locally-sourced seasonal foods. Further studies are required to define more...
precisely optimal sustainable healthy diets for different populations and to ensure that diets are affordable and accessible to people in all countries.

**Key words:** Sustainable healthy diets, flexitarian, territorial diversified diet

**Statement of Significance**

In reviewing the criteria for sustainable healthy diets, we show that flexitarian and territorial diversified diets (TDDs) may offer the optimal balance between human and planetary health without the need for support from healthcare professionals. This is particularly pertinent to those populations at risk of nutritional deficiency from traditional plant-sourced diets such as veganism or vegetarianism. A global switch to flexitarian/TDDs may be a practical and affordable contributor to controlling climate change.

**Introduction**

What we eat has a major impact on our health and the health of our planet. ‘Western-style’ omnivorous diets in high-income countries (HICs) typically comprise large amounts of animal-sourced foods and higher than recommended intakes of energy, saturated fatty acids (SFA), salt, sugar, and refined grains (Table 1), all of which can increase the risk of obesity and other non-communicable diseases (NCDs) [1-3]. In contrast, experience in low-to-middle income countries (LMICs) suggests that without access to certain foods, supplements and nutrition education, predominantly plant-based diets can lead to insufficient energy intake and nutrient deficiencies leading, in turn, to conditions such as stunted growth, delayed development, blindness and reduced functioning [1, 4, 5]. According to the United Nations, unbalanced diets account for approximately 2 billion cases of nutritional deficiencies, 800 million cases of hunger, and 2 billion cases of overweight and obesity, worldwide [1]. This situation is likely to worsen as the global
population grows and as urbanization enables greater, and/or preferential access, access to high-energy, low-nutrient foods [6]. Moreover, global food production accounts for up to 30% of the world’s greenhouse gas emissions (GHGEs), 60% of biodiversity loss, 70% of freshwater use and has a significant impact on soil quality, deforestation, eutrophication (the leaching of nutrients from land into water leading to increased plant and algae growth in estuaries and coastal waters) and climate change [7]. The negative impact of food production on our planet is likely to increase as the population grows [2, 6, 8] and as demand for animal-sourced foods increases in LMICs [1, 9].

The 2015 Paris Agreement on climate change responded to these challenges by highlighting the need for sustainable diets that help ensure the health of the world population and our planet [10]. The four pillars underlying sustainable diets are ‘nutrition and health’, ‘affordability and accessibility’, ‘cultural acceptability’ and ‘environmental impact’ [1]. Modeling studies centered on finding food systems that achieve the best balance between these pillars highlight the need to shift toward diverse, predominantly plant-based diets while concomitantly reducing food losses/waste and improving food production practices [2, 5, 6]. Various organizations including EAT Lancet, the World Health Organization (WHO), Worldwide Fund for Nature (WFN) (formerly World Wildlife Fund), and World Resources Institute (WRI) suggest that these diets should be based on flexitarian or territorial diversified diets (TDD) (e.g., Mediterranean and New Nordic diets) with the option to exclude animal-sourced foods (e.g., vegetarian, pescatarian, or vegan diets) [2, 5, 6, 11-13]. While the different types of diets have not been universally defined, the term ‘flexitarian’ is increasingly used to describe omnivorous diets that incorporate high levels of plant-sourced foods, moderate amounts of poultry, dairy and fish, and low levels of red meat, highly processed foods and added sugar [2, 14, 15]. Vegetarian diets typically include plant-
sourced foods, dairy and eggs but exclude meat and fish; pescatarian diets are vegetarian diets that include fish, and vegan diets exclude all animal-sourced foods including fish, dairy, eggs and honey (Table 1). Based on these definitions, TDDs are region-specific diets that have similar characteristics to flexitarian diets but primarily include seasonal, locally-sourced foods [16]. For some populations (e.g., people consuming western diets in HICs), the transition to flexitarian diets/TDDs requires considerably greater intakes of plant-sourced foods and large reductions in animal-sourced foods (especially red meat), whereas the opposite may be true for people in LMICs.

Recommended food intakes for sustainable healthy diets are typically based on energy and nutrient requirements for an ‘average’ adult [2, 6, 11-13]. However, requirements vary depending on age, sex, pregnancy, and level of activity. Although most organizations recognize this limitation, few provide advice on how to modify the reference diet to suit different populations or how to balance the diet should a population need (or choose) to reduce or exclude one or more food groups due to cultural or religious beliefs, ethical reasons (animal welfare or environmental concerns), food allergies/intolerances, or limited access to certain foods [17]. The aim of this review is to examine the benefits and limitations of the different types of sustainable healthy diets (vegan, vegetarian, pescatarian, flexitarian/TDDs) for different populations in terms of health and nutrition, environmental impact, affordability, accessibility and cultural acceptability, and to suggest ways in which these diets might be adapted to suit the needs of specific populations.
1. What are the benefits and limitations of different types of sustainable diets in terms of health and nutrition?

1.1 Benefits of plant-based diets

The effects of sustainable diets on NCD mortality are unclear, with some studies reporting reductions ranging from 19% with calorie-controlled flexitarian diets to 22% with vegan diets [15, 18] and others reporting no benefits beyond those achieved through calorie control [19, 20]. However, diets that exclude or reduce animal-sourced foods are typically associated with a reduced risk of premature mortality [21] and NCD [1-3, 22-24], primarily due to improvements in cardiometabolic risk factors (insulin resistance/type 2 diabetes [25-27], metabolic syndrome [28], inflammatory markers [29], hypertension [30-32] and dyslipidemia [33-35]), and a reduced risk of certain cancers (e.g., breast [36], prostate [37], and colorectal [38]). In general, the risk of NCDs is lowest for vegans followed by vegetarians, flexitarians and finally western diets [14].

Another benefit for plant-based diets is that they reduce the risk of obesity [25, 39-44]. The Adventist Health Study-2 (N = 96,000) showed a significant association between meat consumption and body mass index (BMI) among adults in the USA and Canada, with the highest BMI among non-vegetarians (mean 28.7 kg/m²) followed by flexitarians (27.3 kg/m²), pescatarians (26.3 kg/m²), and vegetarians (25.7 kg/m²) [25]. Vegans were the only group to achieve a mean BMI in the healthy range (<25 kg/m²). Similar results were obtained from the European Prospective Investigation into Cancer and Nutrition (EPIC) study in Oxford (N = 57,498) [43]. Although reductions in BMI were primarily related to lower intakes of energy-dense SFAs and higher intakes of satiety-promoting fiber, up to 5% of the difference in BMI was attributed...
to the relationship between plant-based diets and weight-loss promoting lifestyle choices, such as increased exercise [45], and reduced alcohol consumption [43, 46].

Overall, results suggest that vegan diets might reduce the risk of premature mortality, NCDs and excessive weight gain. However, the health benefits of any diet partly depend on the variety of foods consumed and the way in which food is stored, processed, and prepared [47]. Variety is important because the chemical and physical properties of individual food components interact to alter our ability to digest, absorb and release nutrients from foods. For example, vitamin C in fruits and vegetables enhances the absorption of non-heme iron from plant-sourced foods [48], whereas lactose and vitamin D increase the absorption of calcium, vitamin B2, vitamin B12, folate, magnesium and zinc [49]. Where possible, fried and/or ultraprocessed high-energy, low-nutrient foods (e.g., animal- and plant-based burgers, cakes and pizzas) should be consumed in moderation [47]. However, some foods (e.g., some processed tomatoes and fermented foods, such as kefir, tempeh, sprouted seeds, kimchi and sauerkraut) are processed in ways that increase their health benefits [50, 51]. In some cases (e.g., beans), the digestibility and bioavailability of essential minerals can potentially be improved by soaking and/or cooking under pressure to reduce levels of anti-nutrients (phytates, polyphenols and tannins) [52], and by ensuring appropriate post-harvest storage and cooking times [53]. Given the benefits and complexities of healthy eating, careful diet planning should be encouraged by promoting lifelong healthy eating strategies in schools, educating families and communities about the benefits and practicalities of meal planning and food preparation, ensuring appropriate health-based dietary guidelines are available in all countries, increasing nutrition training among healthcare professionals, and by increasing public access to registered dietitians/nutritionists.
1.2 Limitations of plant-based diets

Human health depends on the consumption of a wide range of macronutrients and micronutrients, some of which may be difficult to obtain in sufficient quantities from plant sources alone [54, 55]. Compared with omnivorous diets, vegan/vegetarian diets typically contain lower amounts of long-chain omega-3 fatty acids and high-quality proteins (proteins that provide bioavailable essential and branched-chain amino acids when digested [56]), and suboptimal intakes of certain micronutrients, including calcium, vitamin A, riboflavin, niacin, vitamin B12, iodine, selenium, and zinc [15, 23, 54, 57-62]. Although low serum vitamin D concentrations are common irrespective of diet type, risk is higher among people who consume vegan diets or do not consume milk or dairy [63]. While some studies report higher intakes of dietary iron among people who consume vegan and vegetarian diets, plasma ferritin and hemoglobin levels often remain low leading to an increased risk of iron deficiency anemia [62, 64, 65]. This is partly because plant sources predominantly contain non-heme iron, which has a lower bioavailability than animal-sourced heme iron [62], but also because plants contain iron-absorption inhibitors, such as phenolic compounds, oxalates, and phytates [66]. Iron absorption from omnivorous diets is 14-18% compared to 5-12% from vegetarian/vegan diets, thus the recommended daily iron intake for vegetarians and vegans is 1.8-times higher than for omnivores [67]. In addition to iron deficiency anemia, vegan/vegetarian diets have been associated with an increased risk of low birthweight [68-71] and impaired neurocognitive health among infants [72-74], increased risk of stroke among adults [75], impaired vision [74], higher rates of depression [76, 77] and (for vegans) reduced bone mineral density (BMD) [78] and higher rates of bone fracture [79, 80].
1.3 Nutritional benefits of flexitarian diets/TDDs compared with vegan and vegetarian diets

A modeling study designed to assess the nutritional benefits of switching from unregulated diets (i.e., diets that are not carefully planned or recommended by healthcare providers) to well-designed plant-based (vegan, vegetarian, pescatarian or flexitarian) diets found that most of the nutrients that were low during the baseline diets (vitamin A, iron, potassium and fiber) increased to above the WHO-recommended reference nutrient intakes (RNIs) with all four diets (Table 2) [15]. However, vegan diets did not meet RNIs for calcium, and neither vegan nor vegetarian diets met RNIs for vitamin B12. Similarly, a modeling study designed to generate sustainable healthy diets for adults in the Netherlands found that, whereas flexitarian diets met nutrient needs, vegetarian and vegan diets did not provide sufficient omega-3 fatty acids, and the vegan diet only met requirements for vitamin B12 and calcium through high intakes of fortified soy drinks (e.g., two portions per day) [81]. This suggests that, although people who consume vegan/vegetarian diets can achieve their RNIs through careful dietary planning and the use of supplements/fortified plant-based products, RNIs are more easily achieved through flexitarian diets/TDDs. Flexitarian diets may be particularly beneficial for populations that require high intakes of certain nutrients (e.g., children/adolescents and adult females) and for vulnerable populations (e.g., infants, pregnant women and the elderly), for whom nutritional deficiencies are more likely to lead to adverse health issues.

1.3.1 Infants

The WHO advises that infants should be breastfed exclusively for the first 6 months of life and alongside complementary food ideally until 2 years of age [82]. The duration of breastfeeding varies considerably between countries and regions, with some infants not being breastfed at all
and others being breastfed longer than 2 years of age. There is some evidence that the duration of breastfeeding is longer for infants whose mothers follow vegan/vegetarian diets than for other infants, possibly because vegan/vegetarian mothers consider breastmilk to be safer and more natural than other options [83]). Although the energy and nutrient content of breastmilk is largely similar irrespective of the maternal diet [84], breastmilk produced by women consuming vegan/vegetarian diets may contain low levels of B vitamins which may detrimentally impact infant development and neurological function, growth and/or anemia [84-89]. Consequently, lactating women following plant-based diets should not only follow local guidelines on vitamin and mineral supplementation during lactation, but may also need to increase their vitamin B12 intake through supplementation, higher intakes of fortified foods and (for vegetarians/pescatarians) dairy, eggs and/or fish (Table 3) [83, 85, 87, 88, 90, 91]. For women without religious, cultural or ethical restrictions, flexitarian diets/TDDs (particularly Mediterranean diets) that provide high intakes of B vitamins, magnesium, vitamin A, E, C, iron and zinc may reduce the risk of nutritional deficiencies, both for the infant and the mother [92-95]. If breastfeeding is not possible/acceptable, sufficient volumes of infant formulas based on cow/goat-milk or soy can provide the recommended intakes of energy, protein, vitamins and minerals for infants during the first year of life [96].

The proportion of infants in HICs who are fed vegan/vegetarian diets during complementary feeding has increased over recent years, with some countries reporting rates of approximately 10% [83]. Vegan/vegetarian complementary feeding has little effect on height among infants aged 1-3 years, while these infants are less likely to be overweight than their omnivorous counterparts [97, 98]. However, unsupervised vegan/vegetarian weaning (i.e. weaning without the support of educated healthcare providers) may increase the risk of nutritional deficiencies in
infants and children, including deficiencies in omega-3 fatty acids, calcium, iron, zinc, vitamins B12 and vegans vitamin D (Table 3) [83, 99, 100]. Cases of vitamin D deficiency-related bone fracture [100], hypocalcemia leading to seizures, severe anemia, respiratory distress with metabolic alkalosis, growth retardation, and even death have been reported among infants following restrictive diets due to food allergies [99] and inadequate vegan diets without fortified plant-based alternatives [101]. Consequently, professional organizations suggest that parents who wish to wean their infants to vegan/vegetarian diets due to medical (e.g., cow milk allergy), ethical, or religious reasons should follow WHO guidance for vitamin D supplementation [102] and should seek additional guidance from adequately qualified healthcare professionals (HCPs) (e.g., pediatricians and pediatric dietitians) [83, 96, 99, 103-105]. In particular, meat should be replaced with greater intakes of iron- and protein-rich plant-based alternatives, such as pulses, legumes, tofu and nut butters, and fortified flours and cereals should be used in preference (Table 3). Cow’s milk and its derivatives should be replaced with fortified plant-based (soy, oat, nut, coconut, rice, pea, hemp) drinks (suitable only from 1 year of age) and/or yogurts and calcium levels could be augmented by increasing the consumption of low-oxalate green leafy vegetables with high calcium bioavailability, such as kale [106, 107]. While non-organic fortified plant-based alternatives are similar in calcium content to cow’s milk products, these products vary in other micronutrient additions and they are generally lower in energy and significantly lower in protein, except for soy-based alternatives. Ideally a suitable alternative should be recommended by a registered dietitian/nutritionist. Parents should be strongly dissuaded from making their own plant-based drinks, which are nutritionally inferior to those that are fortified.

A survey conducted in Italy found that almost a quarter (22.6%) of all families weaning their infant to vegetarian diets did not consult their pediatrician for nutritional advice and support.
This may be related to the fact that 77% of pediatricians were resistant to alternative complementary feeding styles and 45.2% of families considered their pediatrician was unable to provide sufficient information to support a vegetarian diet for their child. Consistent with these observations, a survey of HCPs found that 79.9% had not attended a nutrition course in the previous five years, 34.1% were unable to correctly define vegetarian/vegan diets, and nutrient knowledge was generally poor [108]. These results highlight the need for greater nutritional education among pediatricians and as the need to develop resources that can adequately support families that choose or (for religious, cultural, or ethical reasons) need to wean their infants to vegan/vegetarian diets. Where possible, families should be referred to a registered dietitian nutritionist.

1.3.2 Children and adolescents

Infants, children and especially adolescents (who experience rapid growth at puberty) require more energy and nutrients per kg of body weight than adults to ensure normal growth rate and development of neural, endocrine, and immunological systems [109, 110]. However, the energy density and (for some nutrients) nutrient density of vegan/vegetarian diets is lower than for omnivorous diets. Consequently, children/adolescents require relatively high intakes of food to meet their recommended energy/nutrient intakes. This might prove challenging for smaller children with limited stomach capacity and for adolescents with very high nutritional demands. Although it is possible for children/adolescents to meet their RNIs through well-planned vegan/vegetarian diets that are often acceptable to this age-group, advice on the suitability of vegan and vegetarian diets for different age groups varies between guidelines, with some suggesting that well-planned plant-based diets are safe throughout childhood and adolescence [90, 111, 112] and others suggesting they should be avoided [99, 103, 113]. If vegan/vegetarian
diets are followed for religious or ethical reasons, appropriate HCP-directed family education and follow-up over time are required to ensure the nutritional needs of the child/adolescent are met.

Primary health concerns for vegan or vegetarian children and adolescents include lower than recommended intakes of vitamin B12 (required for red blood cell formation, nerve function), zinc (growth and sexual development), calcium (skeletal growth), iodine (physical and neurological development), and omega-3 fatty acids (healthy neurological function and eyesight) (Table 3) [109, 114-119]. As for other populations, the incidence of iron deficiency among vegan or vegetarian children and adolescents is high, with the prevalence of low ferritin levels ranging from 4.3% to 73% and the prevalence of low hemoglobin levels ranging from 0% to 47.5% [64]. While vegetarians/pescatarians can increase their intakes of most of these nutrients by increasing their consumption of eggs, dairy and/or fish (Table 3) [118, 120], some guidelines suggest that vegan children and adolescents should be regularly monitored for iron, omega-3 fatty acids, and zinc deficiencies and (as with other pediatric populations) require regular vitamin B12 and D supplements [96].

Consistent with these reports, a study conducted among Dutch children aged 2-6 years (N = 1279) found that diets in which 100% of dairy and meat were replaced with plant-sourced alternatives were associated with a 26% lower SFA intake and 29% higher fiber intake [121]. However, 5-13% reductions in mean intakes of calcium, zinc, and thiamin, a 49% reduction in vitamin B12, and reduced iron bioavailability were also observed. Overall, thiamin, vitamin B12 and zinc intakes from the plant-based diets were lower than the national recommended levels for 15%, 10% and 8% of females aged 4, 5 or 6 years, respectively. In contrast, diets in which
30% of dairy and meat (by gram) was replaced by plant-sourced alternatives potentially improved children’s health by lowering SFA intake by 9% and increasing fiber content by 8%, while maintaining similar micronutrient intakes, with the exception of vitamin B12. This suggests that careful consideration of nutrient intakes is required to ensure that vegan/vegetarian diets meet the needs of growing children and that, for people without religious or cultural restrictions, nutrient adequacy may be easier to achieve with flexitarian diets/TDDs.

1.3.3 Adult females

A study of 62 women aged 18-67 years (78% aged 18-45 years i.e. pre-menopause) found that western and vegetarian diets were associated with significantly greater intakes of SFAs than vegan diets, and that vegan, vegetarian and western diets met the UK-recommended RNI for women [122] in terms of vitamin A, B6, C, E, thiamin, riboflavin, niacin, folates and zinc [54]. However, the vegan group failed to achieve RNIs for iodine, vitamin B12 and calcium, both the vegetarian and vegan groups failed to achieve the RNI for selenium, and all three groups failed to achieve RNIs for iron. Vitamin B12, iodine and calcium levels can be increased among vegan women through supplementation and/or greater intakes of certain plant-sourced foods, including yeast extract, dried fruits/vegetables and fortified cereals to meet vitamin B12 needs, seaweed, peanuts and iodized table salt for iodine, and beans, leafy green vegetables, citrus fruits, nuts and fortified soy drinks, soy alternatives to yogurt and tofu for calcium (Table 3) [54]. However, iodine supplements and iodized salt may not increase iodine concentrations in the blood to adequate levels and iodine is not always fortified in non-dairy drinks [123, 124]. For vegetarian, pescatarian and flexitarian diets/TDDs, each of these vitamins/minerals is readily obtained from dairy, eggs, fish and/or meat. Similarly, while selenium intakes for vegans can be
increased by increasing the consumption of nuts (especially Brazil nuts), pulses and grains, higher concentrations of selenium are available in eggs, dairy, fish and/or meat (Table 3).

Compared with men, women of reproductive age have considerably higher RNIs for iron due to blood losses during menstruation. For vegetarians, lower than recommended levels of ferritin and hemoglobin are observed in up to 79% and 33% of females over the age of 18 years, respectively, compared with 29% and 15% of males [65]. A study in Australian women found that the highest rates of iron-deficiency or anemia were observed among people consuming vegetarian diets (42.6%), followed by flexitarian (38.6%) and finally western diets (25.5%) with rates decreasing with increasing intakes of meat [45]. Although vegan/vegetarian women can increase their iron intake by consuming large quantities of iron-rich foods (e.g., green leafy vegetables, dried fruits, beans, nuts and wholegrains [Table 3]), targets are more likely achieved through the consumption of heme iron, which is only found in meat [62].

1.3.4 Pregnancy

Compared with western diets, plant-based diets in HICs are associated with a reduced risk of excess maternal weight gain during pregnancy, and lower rates of pre-eclampsia [125-127] and gestational diabetes [92-94, 128]. In contrast, vegan diets in HICs have been linked to small-for-gestational-age (SGA) newborns and lower birthweights [68-71], while plant-based diets in LMICs have led to low birthweights, fetal neurological disabilities and malformations [129]. Meta-analysis of data from 111,184 pregnant women found that birth weight and/or length can be significantly increased by increasing the consumption of dairy and that the risks of SGA and low birth weight are inversely correlated with dairy intakes [130]. Further studies are required to determine whether plant-sourced dairy alternatives have similar benefits for vegans.
Nutritional guidelines recommend that all women should receive iron supplements (to avoid anemia) and folic acid supplements (to avoid neural tube defects) before, during and after pregnancy and that increased energy intakes are required from the second trimester [91, 131]. In addition, vegan/vegetarian women are advised to increase their protein intake by approximately 20% to achieve a total intake of 1.1 g/kg body weight per day [132], and to increase their intakes of foods rich in iron, iodine, vitamin B12, calcium and vitamin D, such as dairy/fortified plant-sourced dairy alternatives, green leafy vegetables, dried fruits, fortified cereals, nuts, seeds and (for pescatarians) fish (Table 3) [90, 95]. Flexitarian diets/TDDs (in particular Mediterranean diets) that provide low intakes of total fats and SFAs, high intakes of fiber, folate, zinc, B vitamins, vitamin A, vitamin E, magnesium, and vitamin C are considered ideal for pregnant women [92-94].

1.3.5 Older adults

Compared with western diets, plant-based diets have been associated with improved physical fitness and cognition among elderly populations, and increased longevity [133-135]. Although vegetarian diets are traditionally thought to reduce the risk of osteoporosis through improvements in acid-base homeostasis [136], recent studies suggest that elderly people following vegetarian/vegan diets for more than 10 years have significantly reduced BMD at the femoral neck and lumbar spine than omnivorous counterparts [79, 137], and that vegans have significantly reduced BMD and higher fracture rates than vegetarians [79]. According to public health guidelines, the use of calcium and vitamin D supplements should be considered for people following vegan diets, females >50 years and males >70 years, and for people living in assisted care homes [138]. However, data from more than 51,000 people aged >50 years found
little evidence to support a beneficial association between supplements and bone fractures, leading the authors to conclude that a healthy diet and lifestyle (increased exercise and exposure to sunshine) potentially provide greater protection against bone fractures than supplements [139]. Moreover, observational studies show that the risk of osteoporosis and/or fractures can be reduced in menopausal women through adequate intakes of dietary calcium, high-quality proteins, vitamin B12, vitamin D, and retinol [79, 140, 141]. This suggests that elderly populations are likely to benefit from increased intakes of dairy, fortified plant-sourced drinks, soy/coconut/pea/almond alternatives to yogurt, tofu, grains, legumes, nuts, seeds, eggs and moderate intakes of meat (Table 3). The inclusion of small amounts of meat in the diet will also help maintain vitamin B12 levels, which tend to decrease with age [142].

1.4 Health Benefits of flexitarian diets/TDDs compared with vegan and vegetarian diets

Whereas vegan/vegetarian diets exclude certain food groups, flexitarian diets/TDDs include a diverse range of foods that helps to increase the range of microbial species in our intestinal microbiome [143, 144]. This is important because a diverse microbiome is essential for our digestive, metabolic, immune and mental health, and helps modulate the risk of chronic diseases including obesity, type 2 diabetes, cardiovascular disease, some cancers, inflammatory disorders and autism [145, 146]. Plant-based diets foster greater microbial diversity than western diets due to increased fiber intake [147, 148]. However, diversity can be further increased through the consumption of probiotic and fermented foods (e.g., fermented milk, yogurt, kimchi, soy sauce, tempeh and kefir) and foods rich in omega-3 fatty acids, such as fish [143].

Compared to vegan/vegetarian diets, flexitarian diets/TDDs may have a beneficial effect on mental health. Recent studies suggest that people who consume vegan/vegetarian diets have an increased risk of depression, anxiety and self-harm compared to people who consume meat [76,
However, further work is required to establish whether plant-based diets increase the risk of mental health disorders or whether people with mental disorders choose these diets as a form of self-protective behavior [149]. In particular, patients with eating disorders may be attracted to restricted vegan/vegetarian diets as a means to lose weight and disguise dietary restriction behaviors [150, 151]. This is another reason why appropriate and early dietary monitoring by suitably qualified HCPs is advised for people following vegan/vegetarian diets.

2. What impact do different types of healthy sustainable diet have on greenhouse gas emissions (GHGEs) and the environment?

The effects of food production on climate change have led to decreased agricultural yields and increased food insecurity in some regions of the world [152]. This, together with the burgeoning worldwide population, means current food systems are unsustainable. According to the WRI, a combination of changes will be required to reduce the impact of our diets on the environment, including a shift in our food choices, changes in food production (sourcing and transformation) and reductions in food losses and waste [153].

Food choices

Animal-sourced foods are responsible for more than 60% of food production-related GHGEs, worldwide. However, emissions vary within this food group with meat, fish and eggs accounting for 2- to 3 times more GHGEs per 2,000 kcal of energy than milk and cheese [154], and beef accounting for considerably greater GHGEs per unit of protein or kg of edible food than pork, chicken, fish, eggs and milk (Figure 1) [155, 156]. This is largely because ruminants produce methane, but also because beef cattle produce greater volumes of nitrogen and phosphorus (manure) and require up to 28-times more land than all other animals (including dairy cattle).
combined [157, 158]. This suggests that while the largest reduction in GHGEs can be achieved by excluding meat from our diets, flexitarian diets/TDDs that significantly reduce the consumption of red meat but include moderate intakes of poultry, dairy, eggs and fish might also be effective, albeit to a lesser extent.

Although the ‘footprint’ method of assessing the impact of food production on a single aspect of the environment (e.g., GHGEs, land or water use) is useful, lifecycle assessments (LCAs) that consider the impact of food production, processing, transport, storage, and retail on different aspects of the environment (e.g., climate change, eutrophication, acidification, water scarcity, biodiversity, soil quality, and air pollution) provide a wider picture that should be used to guide our food choices (Figure 2) [153, 159]. According to these assessments, the reductions in GHGEs achieved by shifting from animal-sourced foods to plant-sourced alternatives are often offset by the environmental impacts of transporting out-of-season fruits and vegetables across the world, especially when transported by air [160]. Similarly, the benefits of reducing GHGEs and land use by replacing animal-sourced foods with isoenergetic volumes of nuts, fruits, and vegetables are reduced for plant-sourced foods that are produced in greenhouses or in climates that require large volumes of freshwater for irrigation [161]. This suggests that while animal-sourced foods (especially red meat) have a more negative impact on the environment than plant-sourced foods in terms of GHGEs, the impact of flexitarian diets that respect regionality and seasonality (i.e. TDDs) may be favorable in terms of energy inputs, pollution and water use.

Food production

The global consumption of red meat is projected to increase from approximately 190 million metric tons (MMT) in 2018 to more than 376 MMT by 2030 [55]. To meet this demand, the
expansion of cattle farms has led to large-scale deforestation in some of the most biodiverse regions of the world with devastating effects on climate change and biodiversity [6, 162]. Whereas only 9% of meat is produced using grazing systems, 46% is produced using intensive systems that require large volumes of high-energy plant-sourced foods, such as soy and alfalfa [163]. This is important because the production of animal feeds increases the requirement for land, fertilizer and water and places cattle in direct competition with humans for nutrition. Converting animal feed to animal-sourced food is also highly inefficient, with as few as 3% of the plant calories in feed converted to calories in beef [164]. In addition to land and water use, the expansion of livestock and cattle feed farms has led to eutrophication of freshwater rivers and lakes, and acidification of seawater due to nitrogen and phosphorus leaching from manure and excessive use of fertilizers on animal feed farms [165]. Although the environmental impact of animal-sourced foods can be reduced by reducing our consumption of red meat, further benefits can be gained from changes in farming practices, such as recycling manure as fertilizer for crops, converting manure into biogas and/or feeding cattle on grasslands instead of (or alongside) animal feeds.

In terms of plant-sourced foods, agricultural practices increasingly rely on the use of chemical fertilizers to restore nutrients to the soil, thereby enabling farmers to plant just one crop, without the need for rotational cropping (i.e. monocropping) [166]. Although monocropping can result in higher food yields and lower prices in the short term, it is also associated with deforestation, poor soil quality, and reduced biodiversity and food security in the long term [167]. Organic farming (which uses ecologically-based pest control and fertilizers derived from animal/plant waste and nitrogen-fixing crops) can help improve soil quality, prevent soil erosion and reduce the risk of eutrophication and water contamination due to nitrate, phosphate and
chemical leaching from the soil while recycling plant and animal waste [168]. However, the benefits of organic farming are typically offset by the need for more land due to lower yields. Mixed farming strategies that combine animal farms with crop agriculture can improve our land use while enabling farmers to recycle plant and animal waste into natural fertilizers for crops, thereby reducing the need for chemical fertilizers and reducing eutrophication. Overall, data suggest that the environmental impact of foods varies depending on the way in which they are produced and that the impact of both animal-sourced foods and plant-sourced foods can be reduced by changing the way in which food is produced.

Food losses and waste
Food losses (food lost during production) and food waste (food produced, but not used) have a major impact on the environment [169, 170]. Food losses are more common in LMICs than in HICs due to increased rates of animal mortality, crop failure and inadequate farm storage facilities [170]. In contrast, food waste is 5 to 10-fold greater per person in HICs than in LMICs, with Europe and North America wasting 18–30 kg of meat per person per year in 2013 compared with 2-5 kg in sub-Saharan Africa and South/Southeast Asia [171]. In the USA, consumers waste an average of 422g of food per person per day, which amounts to 25% of daily food production by weight, 30% of available calories, 4.2 trillion gallons of wasted irrigation water, 3.3 billion pounds of wasted nitrogen/phosphorus fertilizer, and 30 million acres (>120,000 km²) (7%) of wasted cropland per year [169]. Globally, the amount of food wasted each year is sufficient to feed nearly 2 billion people a 2,100 kcal/day diet [172].

Compared with animal-sourced foods, plant-sourced foods (especially fruits and vegetables) are associated with greater food waste, but less land waste [169, 173, 174]. Consistent with this
observation, a study conducted among Canadian families found that daily per capita fruit and vegetable waste increased as the quality of the parental diet improved [174]. This highlights a need to educate people (particularly those in HICs and/or those people who eat a healthy plant-based diet) about the impact of waste on the environment, the need to balance food purchases with needs, and how to prepare and store (e.g., freeze) perishable foods [175].

Environmental impact of diet type

Studies suggest that the environmental impact of food production is higher for omnivorous diets and lower for vegetarian/vegan diets. For example, meta-analysis of data from 25 studies focusing on the effects of food production on GHGEs found that, compared with omnivorous diets, vegetarian and vegan diets reduced median GHGEs by 35% (range 13% to 85%) and 49% (23% to 89%), respectively, while reducing land use by 42% (27% to 74%) and 49.5% (29% to 80%) [156]. Although vegetarian diets were associated with reduced water use (median 28%; range 7% to 52%), the effects of vegan diets varied, with one study showing a reduction of 22% and others showing increases ranging from 1% to 107%. Consistent with these data, a modeling study examining the environmental impacts of different dietary scenarios across 150 countries found that transitioning to sustainable healthy diets reduced GHGEs by 54% (flexitarian diets) to 87% (vegan diets), with moderate to small reductions in nitrogen application (23–25%), phosphorus application (18–21%), land use (8–11%) and freshwater use (2–11%) (Figure 3) [15]. However, whereas GHGEs and nitrogen application were reduced in all countries, land use, freshwater use, and phosphorus applications were reduced in high- to middle-income countries, but increased in low-income countries (LICs) due to differences in crop yields and agricultural inputs (fertilizers, pesticides, and irrigation).
Overall, data suggest that vegan/vegetarian diets are likely to have less impact on the environment than flexitarian diets/TDDs. However, flexitarian diets/TDDs that include very low intakes of red meat, moderate intakes of poultry, eggs and dairy, and a wide range of seasonal, locally-produced plant-sourced foods grown using mixed-farming techniques will have a lower impact on the environment than western diets.

3: What are the benefits and limitations of different sustainable healthy diets in terms of affordability, accessibility, and cultural acceptability?

3.1 Affordability and accessibility

Accessibility and affordability of nutritious diets vary between countries. According to the United Nations, approximately 26% of the world population does not have regular access to nutritious foods and currently experiences food insecurity, whereas wealthier populations have access to excessive amounts of food leading to high rates of obesity and large volumes of waste [176]. For example, vegetables, fruits and certain nuts (excluding peanuts) that are high in essential nutrients are often less affordable in LMICs than in HICs. Moreover, more than 40% of all red meat produced globally in 2018 was consumed in HICs by less than 25% of the world’s population [171]. Greater efforts are required to ensure that affordable and nutritious foods are evenly distributed across the world.

According to food prices for 159 countries, the minimum daily cost in US$ of EAT Lancet diets in 2011 ranged from $2.42 per person in LICs to $2.66 in HICs, with the greatest costs attributed to fruits and vegetables (31.2%), legumes and nuts (18.7%), meat, eggs and fish (15.2%), and dairy (13.2%) [177]. This suggests that sustainable healthy diets account for a small proportion of
average income in HICs and are generally similar or less expensive than national diets [13, 178, 179]. In contrast, EAT Lancet diets can be 1.5-times more expensive than the cheapest nutritional diet in LICs [180], with costs exceeding income for approximately 1.6 billion people in the developing world. A study assessing food prices in Switzerland in 2011 found that vegetarian and flexitarian diets were slightly cheaper than vegan and pescatarian diets (Figure 4) [179]. However, further studies are required to determine whether this relationship applies to other countries.

3.2 Acceptability

The acceptability of different foods depends on nutritional and environmental factors as well as functionality (convenience, availability, packaging, durability), socialization (family, friends, habits), sensory attributes (taste and texture), culture (traditions, religions), and context (place, time, and company) [55]. However, people’s notions of acceptability vary between countries and cultures. Whereas plant-based diets and dairy are generally acceptable in LMICs, meat is often excluded from the diet due to cultural, financial, ethical and/or religious reasons [4]. In contrast, people in HICs often consider meat to be an important part of a meal and believe vegetarian/vegan diets to be inconvenient, difficult to prepare and less enjoyable than omnivorous diets [181, 182]. Whereas consumers in Europe are moderately open to substituting meat with dairy, fish and eggs, they are less keen to replace meat with plant-sourced alternatives and even more unwilling to try novel foods, such as insects or synthetic meat [183, 184]. In the USA, up to 84% of people transitioning from western diets to vegan/vegetarian diets eventually revert back to their original diet, with 53% giving up after one year [185]. For these people, flexitarian diets/TDDs that include a wider range of foods than vegan/vegetarian diets can provide an easier transition to sustainable healthy diets, due to increased availability and
convenience in HICs and because there is no need to exclude certain foods, making it easier to share and enjoy mealtimes with people who eat omnivorous as well as plant-based diets [32, 186]. Moreover, flexitarian diets/TDDs enable the use of animal sources as a minor part of a meal or as seasoning in order to provide the tastes that humans seek (umami, salt, fat), but cannot easily obtain from ‘neutral’ tasting plant-sourced foods [187, 188]. Overall, evidence suggests that flexitarian diets/TDDs are more acceptable and easier to sustain in HICs than vegetarian/vegan diets, whereas the opposite might be true for some LMICs. However, trends are changing in both regions [9, 189].

4. Sustainable healthy diets should be optimized for different populations
Diet modelling studies show that the number and types of food items that need to be changed to achieve sustainable healthy diets vary between countries depending on baseline diets, food availability/preferences, local culture and traditions, and national targets [4, 54, 190, 191]. To minimize the number of food changes (thereby maximizing acceptability and the likelihood of long-term compliance with recommended dietary changes), sustainable healthy diets are often optimized for different countries [12, 13, 33, 81, 179, 192-200]. Most sustainable, healthy diets are based on energy/nutrient requirements for the ‘average’ adult/adult male [2]. However, energy and nutrient requirements vary between populations and, without careful adjustment, recommended diets might not be suitable for populations with different energy or nutrient needs. Consequently, modelling studies are beginning to emerge that optimize country-specific sustainable healthy diets for different populations. Population-specific recommendations are available for children over 9 years of age, adolescents, adult females, the elderly and vegans [12, 54, 201-203]. Further studies are required to optimize sustainable healthy diets for other
populations, including infants, young children, pregnant and/or lactating women, vegetarians, pescatarians, flexitarians and people following TDDs.

Conclusions

Traditional plant-based diets (vegan/vegetarian/pescatarian diets) are consumed by large numbers of people who wish to reduce their intake of animal-sourced foods due to religious, cultural, health or ethical (i.e. animal welfare and/or environmental) reasons. Compared with western diets, plant-based diets can reduce the risk of obesity, NCDs and premature mortality while reducing the impact of food production on the environment (Table 1). However, without professional supervision, traditional plant-based diets, i.e. vegan/vegetarian/pescatarian diets, can also increase the risk of nutritional deficiencies mainly among infants, children/adolescents, adult females, pregnant and/or lactating women and the elderly. Greater efforts are required to ensure that HCPs receive adequate nutritional training and that nutritional support is available for people following these diets across the world.

Unlike vegan/vegetarian/pescatarian diets, predominantly plant-based flexitarian diets/TDDs can meet the energy and nutrition needs of different populations without the need for dietary education or supplementation (Table 1). Moreover, studies suggest they have a more sustainable impact on the environment than western diets (especially if diets include locally-sourced seasonal foods), and may be more acceptable and easier to maintain than less diverse vegan/vegetarian/pescatarian diets for people transitioning from western diets to sustainable healthy alternatives. Further studies are required to define more precisely optimal sustainable healthy diets (taking into account the four pillars underlying these diets) for different populations and to ensure that diets are accessible to people in LMICs as well as in HICs. Ensuring the
adoption and maintenance of healthy sustainable diets will require educating all stakeholders (including families, HCPs, governments, food industries, and marketing companies) about the need for sustainable healthy diets, providing guidance to tailor sustainable healthy diets according to the energy/nutritional requirements of specific populations, while reducing food waste, and ensuring the food system can provide different types of affordable, nutritious foods across all regions of the world.

Acknowledgements: Editorial assistance for the preparation of this article was provided by Jackie Read PhD from Chill Pill Media Ltd., funded by Danone Institute International (a non-profit organization). All authors (LM, RM, SD, OG, JH, FK, PVV) contributed to read and approved the manuscript.

Conflicts of interest: OG is a member of the board of Danone Institute International, a non-profit organization. OG, SD, and FK are members of the Scientific Advisory Board of the Yogurt In Nutrition Initiative for Sustainable and Balanced Diets (YINI) which is funded by the Danone Institute International. LM is past member of the Scientific Advisory Board of the YINI. SD has received support for attending meetings and/or travel from Danone Institute International, consulting fees from Danone Institute International in her role as a YINI Board member, The Dannon Company, ByHeart, Alcimed, and Austnutria, and payment or honoraria for lectures, presentations, speakers’ bureaus, manuscript writing or educational events from The Beef Council, Austnutria, Danone Institute International, and PRIME education. Grants have been paid to SD’s institution by the NIH, USDA, National Dairy Council, Nestle Nutrition, Mead Johnson Nutrition, the Dannon Company, The Gerber Foundation, IFF, Kyowa Hakka Bio, and Triton Algae Innovations. JH reports grants or contracts paid to her institution by the Canadian Institutes for Health Research, Danone Institute North America, Health Canada, and the NIH. JH has been awarded the 2021 Danone International Prize for Alimentation. She has also received an honorarium from Danone Institute International for presenting at an international meeting and support for attending meetings from Health Canada, Danone Institute International, and the Canadian Nutrition Society. PVV has received research grants for a TiFN-coordinated Public
Private Partnership (2015-20), and a grant from the Dutch Dairy Association (2020-2021). He also reports payments or small honoraria for public presentations, manuscript writing or educational events from Danone Institute International. RM reports consulting fees and payment or honoraria for lectures, presentations, speakers’ bureaus, manuscript writing or educational events from Abbott Laboratories, Nutricia/Danone, Nestle and Mead Johnson.

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| Diet | Definition | Benefits | Limitations | Suitable for? |
|------|------------|----------|-------------|---------------|
| Western-style diet | Omnivorous diet\(^1\) that typically includes high intakes of animal-sourced foods, highly processed foods and lower-than-recommended intakes of plant-sourced foods \(^2\) | • Affordable and easily accessible in HICs; increasingly accessible in LMICs | • Higher than recommended intakes of energy, saturated fatty acids, salt, sugar, and refined grains | • Not ideal for anyone |
| Flexitarian diet | Omnivorous diet\(^1\) that includes high levels of plant-sourced foods (e.g., fruits, vegetables, unrefined grain, legumes, nuts and seeds), moderate amounts of poultry, dairy and fish, and low levels (one serving per week) of red meat, highly processed foods and added sugar \(^2\,14,15\) | • Reduced risk of obesity and NCDs compared to western diets | • Might not be affordable/accessible in some LMICs | People wishing to transition from a western diet to a sustainable healthy diet who might struggle to maintain vegan/vegetarian/pescatarian diets |
| Territorial diversified diet (TDD) | Flexitarian-style diet that includes high intakes of seasonal, locally-produced foods (e.g., Mediterranean diet, New Nordic diet) \(^16\) | • As for flexitarian diets | • Might not be appropriate for certain populations due to religious, cultural or ethical beliefs that exclude flexitarian diets | As for flexitarian diets |
| Vegetarian diet | Excludes meat, fish/shellfish, insects, and gelatin but includes plant-sourced foods and (usually) dairy and eggs \(^23\) | • Reduced risk of obesity and NCDs compared to western diets | • Environmental impact may be reduced compared to some flexitarian diets due to the inclusion of large quantities of seasonal, locally-sourced foods | As for flexitarian diets |
| Pescatarian diet | Vegetarian diet that includes fish/shellfish | • Reduced risk of obesity and NCDs compared to western diets | • Unsupervised pescatarian diets are associated with an increased risk of energy/nutritional deficiencies compared to pescatarian/flexitarian diets | People wishing to transition from a western diet to a sustainable healthy diet who might struggle to maintain a vegan diet or have religious, cultural or ethical beliefs that exclude flexitarian diets |

\(^1\) Based on the European Food Safety Authority (EFSA) recommendations.

\(^2\) Based on the World Health Organization (WHO) recommendations.

HICs: High-income countries; LMICs: Low-income countries; NCDs: Non-communicable diseases.
| Diet                | Description                                                                 | Benefits                                                                                      | Challenges                                                                 |
|---------------------|-----------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|---------------------------------------------------------------------------|
| Vegan diet          | Excludes all animal products including meat, fish/shellfish, insects, eggs, dairy, and honey [23] | - Reduced risk of obesity and NCDs compared to western diets  
- Reduced environmental impact compared to western diets  
- Affordable and accessible for most people in HICs | - May be less affordable/accessible for some LMICs than vegetarian/flexitarian diets  
- Professional nutritional advice, supplements and fortified foods are required  
- Well-planned vegan diets may be less affordable/accessible for some LMICs than vegetarian/flexitarian diets  
- May (for some) be less acceptable and harder to maintain than more diverse diets |

1Diverse diet that includes all types of meat, fish/shellfish, dairy, eggs, honey, insects, and plant-sourced foods (e.g., fruits, vegetables, grains, pulses, legumes, nuts, seeds, tubers, fungi, algae) in any ratio; 2Lacto-ovo-vegetarian diets include dairy and eggs; lacto-vegetarian diets include dairy, but not eggs; ovo-vegetarian diets include eggs but not dairy. HIC, high-income country; LMIC, low-to-middle-income country; RNI, recommended nutrient intake.
Table 2. Nutrient supply per day by dietary scenario for the ‘average’ person across 150 countries, worldwide, in 2010.

| Nutrient            | Recommendation¹ | Diet scenario |          |          |          |
|---------------------|-----------------|---------------|----------|----------|----------|
|                     |                 | Flexitarian   | Pescatarian | Vegetarian | Vegan    |
| Calories, kcal      | 2084            | 2084          | 2084     | 2084     | 2084     |
| Protein, g          | >52             | 70.6          | 72.5     | 65.0     | 64.7     |
| Carbohydrates, g    | <391            | 274           | 278      | 289      | 304      |
| Fat, g              | ..              | 81.8          | 78.1     | 77.3     | 71.3     |
| Saturated fatty acids, g | <23 | 19.7          | 17.5     | 17.2     | 13.4     |
| Monounsaturated fatty acids, g | .. | 31.4          | 28.1     | 27.7     | 26.1     |
| Polyunsaturated fatty acids, g | >14 | 27.7          | 27.2     | 27.4     | 27.6     |
| Vitamin C, mg       | >42             | 148           | 163      | 171      | 196      |
| Vitamin A, µg       | >544            | 627           | 679      | 694      | 703      |
| Folate, µg          | >364            | 553           | 577      | 644      | 733      |
| Calcium, mg         | >520            | 621           | 660      | 630      | 489      |
| Iron, mg            | >17             | 18.8          | 19.3     | 19.5     | 21.1     |
| Zinc, mg            | >6·1            | 10.4          | 10.4     | 10.2     | 10.3     |
| Potassium, mg       | >3247           | 3383          | 3555     | 3634     | 3952     |
| Fibre, g            | >29             | 35·5          | 36·6     | 39·9     | 44·6     |
| Copper, mg          | >0·8            | 2·3           | 2·3      | 2·5      | 2·7      |
| Phosphorus, mg      | >757            | 1379          | 1429     | 1366     | 1337     |
| Thiamin, mg         | >1·1            | 1·5           | 1·5      | 1·5      | 1·6      |
| Riboflavin, mg      | >1·1            | 0·9           | 1·0      | 0·9      | 0·9      |
| Niacin, mg          | >14             | 17·5          | 17·4     | 16·0     | 16·8     |
| Vitamin B6, mg      | >1·2            | 6·1           | 6·2      | 6·1      | 2·3      |
| Magnesium, mg       | >205            | 527           | 543      | 561      | 596      |
| Pantothenate, mg    | >4·7            | 5·4           | 5·4      | 5·3      | 4·9      |
| Vitamin B12, µg     | >2·2            | 2·4           | 3·7      | 0·8      | 0·0      |

Adapted with permission from reference [15] under the terms of the Creative Commons CC-BY license.

¹Recommended nutrient intakes are based on WHO guidelines [204] for all nutrients other than phosphorus and copper, which are based on recommendations from the US Institute of Medicine [205]. Because the recommended nutrient intakes differ by age and sex, population-level average values were calculated using the age and sex structure based on data from the Global Burden of Disease project and forward projections by the UN Population Division. Estimates of recommended energy intake account for the age-specific and sex-specific energy needs for a moderately active population with US height as an upper bound and include the energy costs of pregnancy and lactation.
### Table 3 Energy/nutrient inadequacies and dietary advice for different populations following vegan, vegetarian, pescatarian, or flexitarian diets/TDDs

| Nutrient                          | Function                                                                 | Food sources                                                                 | Advice                                                                 |
|----------------------------------|--------------------------------------------------------------------------|------------------------------------------------------------------------------|-----------------------------------------------------------------------|
| **Good-quality proteins**        | Involved in a wide range of metabolic interactions; essential for growth and repair; help maintain healthy skin, bones, muscles and organs [206, 207] | Eggs, milk and dairy products; soy products; meat substitutes; legumes; lentils; nuts; seeds; selected whole grains [207] | People following vegan /vegetarian /flexitarian/TDD diets should aim to replace meat protein sources with high quality protein alternatives. To ensure nutritional adequacy, HCP advice may particularly be required for young children and pregnant women |
| **Calcium**                      | Helps develop and maintain healthy teeth and bones; vital roles in intracellular signaling for metabolic regulation, information transmission via the nervous system, muscle contraction, and blood clotting [206, 208] | Milk and dairy products; low-oxalate green leafy vegetables with high calcium bioavailability, such as kale [106, 107]; calcium-enriched plant-based milks and products (e.g., soya milk, yoghurt, oat milk and yoghurt, coconut milk and yoghurt, and tofu); calcium-enriched juices; fortified cereals; sesame paste (tahini); almonds; seaweed and figs [206] | If insufficient calcium-enriched plant-based alternatives are consumed, HCP advice needs to be sought to advise a suitable calcium supplement |
| **Omega-3 fatty acids**          | Essential fatty acid that must be supplied by diet; important components of cell membranes; substrates for signaling molecules that control cellular functions; important for heart health [206, 209] | Oily fish; omega-3 enriched eggs; canola/rapeseed oil; walnuts; ground flaxseed; hemp seed; chia seed; fortified products [206] | If no fish is consumed (i.e. vegan, vegetarian diet) HCP advice may be required to advise on vegetarian sources of docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) and suitable supplementation may be needed |
| **Iron**                         | Component of hemoglobin in red blood cells, allowing oxygen transportation; important roles in the immune system; required for energy and drug metabolism [206, 208] | Heme sources: beef, liver; Non-heme sources: dried beans and peas; lentils; enriched cereals; nuts and seeds; selected whole-grain products; dark leafy green vegetables but bioavailability can be low due to phytate and tannin content [206]. Eating foods rich in vitamin C helps absorb non-heme iron [206] | In high-risk population (i.e. young children and during pregnancy), an iron supplement may be needed if intake of non-heme/heme alternatives do not meet iron requirements. |
| **Zinc**                         | Co-factor for many enzymes involved in digestion, carbohydrate and bone metabolism, oxygen transport, immune response, stabilizing the structure of DNA, RNA and ribosomes [210] | Beef; crab and shellfish; lamb; leafy or root vegetables; whole grains; pork; poultry; milk and dairy products; eggs; nuts; offal [210]. Foods high in phytates (e.g., whole grains) reduce the bioavailability of zinc | In high-risk populations (i.e. young children), and in particular if growth is affected, a zinc supplement may be required |
| **Iodine**                       | Maintenance of metabolic rate controlling energy production and oxygen consumption; growth and cognitive development; protein metabolism in fetuses/neonates [210] | Milk and dairy products; sea fish; seaweed; iodized salt, local iodine fortified foods [210] | In particular, young vegan children may need an iodine supplement, as salt intake should be limited in the young |
| **Selenium**                     | Protects against oxidative damage; antioxidant and                         | Offal; fish; brazil nuts; eggs; poultry; meat                               | HCP advice may be required to assess need for                                |
| **Vitamin A**<br>(retinol; beta-carotene) | Involved in adaptation of vision in the dark; growth; cell differentiation; embryogenesis; immune response [210] | Retinol: Liver products; kidney; offal; oily fish and fish liver oils; eggs. Beta-carotene: Carrots; red peppers; spinach; broccoli; tomatoes [210] | There are many sources of plant-based alternatives for vitamin A, however availability of these alternatives needs to be considered in conjunction with local prevalence of vitamin A deficiency. HCP advice may be useful on whether supplementation is required. |
|---|---|---|---|
| **Riboflavin**<br>(B2) | Oxidation-reduction reactions in metabolic pathways; promotion of normal growth; assists synthesis of steroids, red blood cells and glycogen; maintenance of mucous membrane, skin, eyes and nervous system; aids iron absorption [210] | Eggs; milk and dairy products; liver; kidney; yeast extract; fortified breakfast cereal [210] | Ensure that nutritional alternatives are consumed, in particular in individuals who follow vegan diets. |
| **Niacin**<br>(B3) | Glycolysis; fatty acid metabolism; detoxification | Beef; pork, chicken; wheat flour; maize flour; eggs; milk and dairy products [210] | Ensure that nutritional alternatives are consumed, in particular in individuals who follow vegan diets. |
| **Vitamin B12**<br>(cobalamin) | Recycles folate coenzymes; normal myelination of nerves; synthesis of methionine from homocysteine [210] | Meat products; eggs; milk and dairy products; fish products; yeast products; fortified vegetable extracts; fortified breakfast cereal [210] | HCP advice may be required, in particular if a vegan diet is followed. A B12 supplement may be required. |
| **Vitamin D**<br>(calciferols) | Calcium absorption and excretion; involved in bone mineralization; may inhibit cell proliferation in some forms of cancer [210] | Cod liver oil; oily fish; fortified milk and dairy products; fortified margarine; fortified breakfast cereals; eggs (in particular egg yolk); liver | The WHO supports routine supplementation for a wide range of populations [204]. Local advice for vitamin D supplementation should be followed and the increased risk of vitamin D deficiency with a plant-based diet should be considered. |

HCP, healthcare professional; TDD, territorial diversified diet
Figure 1. Greenhouse gas emissions in the production of foods. Adapted with permission from reference [155].

Values shown in the boxplots are minimum and maximum values, IQR (rectangle borders) and median (line inside the rectangle). CO$_2$e, CO$_2$ equivalents; N, number of studies included.
Figure 2. The food life cycle and burden on environmental resources.

GHGE, greenhouse gas emissions; HIC, high-income countries; LMIC, low-/middle-income countries
Figure 3: Percentage change in environmental impacts for different diet scenarios worldwide in 2030. Adapted with permission from reference [15] under the terms of the Creative Commons CC-BY license.

Environmental impacts were estimated using a model that combines regional food consumption, production and country-specific environmental footprints for greenhouse gas emissions, cropland use, freshwater use, and nitrogen and phosphorus application, taking into account trade, feed, and processing of primary commodities. The model was calibrated using data from the IMPACT agriculture-economic model.
Figure 4. Cost of nine diet scenarios relative to the current diet (REF = 100%). Adapted with permission from reference [179] under the terms of the Creative Commons CC-BY license.

FXT, flexitarian; HGD, healthy global diet; MTO, meat oriented; PST, pescatarian; PTO, protein oriented; REF, reference diet; RSN, recommendation of Swiss Society in Nutrition; TAX, food greenhouse gas tax diet (TAX); VGN, vegan; VGT, vegetarian.