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Vegan diets: A critical review of nutritional quality and health implications

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Abstract
Vegan diets, characterized by the exclusion of all animal-derived foods, have gained global prominence due to their perceived health benefits, ethical considerations, and reduced environmental impact. This review examines the nutritional, metabolic and environmental dimensions of vegan dietary patterns, with particular emphasis on nutrient bioavailability, food matrix effects and the growing role of ultra-processed plant-based foods. Evidence indicates that well-planned vegan diets are associated with a lower risk of chronic conditions such as type 2 diabetes and cardiovascular diseases, primarily due to higher intakes of dietary fibre, antioxidants, and unsaturated fats. However, concerns remain regarding the adequacy and bioavailability of key nutrients, including vitamin B12, iron, calcium, zinc, and omega-3 fatty acids, which may be limited or less efficiently absorbed from plant sources. The increasing consumption of plant-based meat and dairy alternatives, often classified as ultra-processed foods, further complicates the nutritional landscape, as these products exhibit variable nutrient profiles despite their functional and sensory advantages. From an environmental perspective, vegan diets consistently demonstrate lower greenhouse gas emissions, land use, and water demand compared to animal-based dietary patterns, although the sustainability benefits are influenced by food choices within the diet. Overall, the health and environmental outcomes of vegan diets depend not only on the exclusion of animal products but also on overall diet quality, appropriate food selection, and nutritional planning. Future research should focus on long-term health effects, improvements in food processing technologies, and strategies to enhance nutrient bioavailability in plant-based systems.

Keywords: Vegan diet; plant-based nutrition; nutrient bioavailability; ultra-processed foods; health outcomes; carbon footprint; micronutrient deficiencies

Introduction

Vegetarianism has become increasingly popular in recent years and includes a range of dietary patterns that differ in the extent to which animal foods are excluded. Veganism is a dietary and lifestyle practice that excludes all foods derived from animals, whether directly or indirectly [1, 2]. Vegans follow the most restrictive form, avoiding all foods of animal origin, including their by-products. Accordingly, vegan diets exclude eggs, dairy products, meat, and other animal-derived ingredients in their diet, including honey, collagen, and gelatine. Other types of vegetarianism include lacto-vegetarians, who consume dairy products but exclude meat, fish, and eggs; ovo-vegetarians, who include eggs but avoid meat, fish, and dairy; lacto-ovo-vegetarians, who consume both dairy and eggs but exclude meat; and pescatarians, who avoid meat but include fish and shellfish [1, 3, 4]. The perception of vegetarian diets has shifted markedly over time. Initially considered nutritionally inadequate, they were later associated with reduced risk of chronic diseases despite persistent scepticism [5]. The concept of veganism, formally termed by Donald Watson in 1944, has deeper roots in ancient traditions such as the principle of “Ahimsa” in Indian religions and early philosophical advocacy by Pythagoras, reflecting a long-standing emphasis on non-violence and plant-based living [6].

The shift toward plant-based diets is driven by a combination of health, ethical, and environmental considerations. Additionally, medical conditions such as lactose intolerance and cow’s milk protein allergy have contributed to the growing demand for plant-based alternatives, particularly plant-based milk products [7]. Global dietary trends indicate a substantial reduction in meat consumption, with a 2018 survey in the United States reported that nearly two-thirds of respondents had reduced their meat consumption over the previous three years. Similar patterns are observed in the United Kingdom, where 21% of the population is identified as flexitarian, while approximately one in eight individuals reported being either vegetarian or vegan. Similarly, Germany saw an increase in its vegetarian population from 1% in 2005 to 7% in 2018. In Italy, the number of people following a meat-free diet rose by 94.4% between 2011 and 2016, and in Spain, the proportion of flexitarians grew by 25% within a span of two years [8]. This global shift toward reduced meat consumption is further reinforced by recent consumer surveys from 2025–2026, which demonstrate increasing acceptance of alternative proteins, with approximately 75% of global consumers expressing interest in plant-based options—particularly when these products closely replicate the organoleptic properties of meat [9].

This dietary transition is paralleled by rapid expansion of the plant-based food market. The global market for plant-based meat alternatives is projected to increase from USD 1.6 billion in 2019 to USD 3.5 billion by 2026 [10]. According to a 2020 report by Fortune Business Insights, the global vegan products market was valued at approximately USD 15.77 billion and is projected to reach around USD 31.4 billion by 2026 [11]. In an early outlook on global market trends, *The Economist* predicted that 2019 would mark the mainstream emergence of veganism [12]. This prediction was widely reflected in business and cultural discourse, with growing emphasis on launching vegan enterprises and adapting existing companies to plant-based models [13].

In India, the vegan food market is also experiencing notable growth, driven by a rising vegan population. The increasing demand for plant based alternatives has also encouraged the development of innovative functional foods that address nutritional and sensory limitations associated with conventional vegan products. Synbiotic beverages, which combine probiotic microorganisms with prebiotic components, represent a promising category of plant based functional foods. A study developed plant based milk synbiotic beverages using sunflower seeds, little millet and tender redgram as alternatives to dairy milk. The beverages were prepared by incorporating honey as a prebiotic source and fermenting with ABT probiotic culture containing *Lactobacillus acidophilus*, *Lactobacillus delbrueckii* subsp. *bulgaricus* and *Streptococcus thermophilus*. The developed beverages demonstrated good probiotic viability, nutritional quality with higher protein and crude fibre content, acceptable sensory characteristics and storage stability, highlighting their potential as affordable plant-based functional food options [14]. In this context, the present review aims to critically evaluate the nutritional adequacy, health outcomes, and environmental implications of vegan diets, with particular emphasis on nutrient bioavailability, ultra-processed foods, and sustainability.

Nutritional Effects of Vegan Diets

Transitioning to a vegan diet without careful consideration of macronutrient distribution may lead to a significant reduction in protein intake and a corresponding increase in carbohydrate intake. A controlled 12-week study in young recreationally trained women transitioning from an omnivorous to a vegan diet reported reduced protein intake (from 15.5% to 13.6% of total energy), alongside an increase in carbohydrate intake (from 45% to 53.6%). This shift in macronutrient distribution was associated with a significant reduction in body weight and a slight decline in skeletal muscle mass, suggesting that the relatively lower protein intake and potentially suboptimal amino acid profile of plant-based diets may have contributed to diminished muscle maintenance [15]. However, reduced muscle mass cannot be directly attributed to a plant-based diet itself, as emerging evidence suggests that adequate protein intake, when appropriately planned, can support muscle adaptations comparable to those achieved with animal-based proteins [16]. A likely limiting factor in adopting a vegan diet is the practical challenge of implementing dietary recommendations in everyday life [17].

Although animal products are well-recognized sources of protein, the adequacy of protein intake from vegetarian and vegan diets has long been a subject of debate [18]. While total protein intake may be sufficient, differences in digestibility and amino acid composition can affect protein utilization. For instance, a simulation study in older adults demonstrated that transitioning to flexitarian, pescetarian, or vegetarian diets resulted in a modest reduction in utilizable protein (approximately 5%), whereas a vegan diet was associated with a substantially greater reduction of nearly 50% [19].

Proteins derived from pulses, such as peas and chickpeas, are typically limited in sulphur-containing amino acids, including cysteine (Cys) and methionine (Met), as well as tryptophan (Trp), whereas cereals, nuts, and seeds—such as flaxseed—are generally low in lysine (Lys) [20]. However, strategic combination of diverse plant protein sources can provide a complete amino acid profile [21], and when such complementarity is achieved, plant-based diets can support muscle protein synthesis to a comparable extent as animal-based diets. In contrast, some studies have reported lower circulating levels of essential amino acids, including lysine (Lys), cysteine (Cys), and methionine (Met), in individuals following a vegan diet compared to those consuming a meat-based diet, suggesting that differences in dietary amino acid composition may be reflected in circulating blood profiles [22].

Overall, adequate protein intake in vegan diets is achievable but requires careful planning to ensure both sufficient quantity and quality.

Bioavailability and Food Matrix Effects

A well-planned vegan diet has been widely recognized for its potential health advantages, with substantial evidence indicating that it may lower the risk of various chronic diseases [23]. Conversely, insufficient intake of essential nutrients such as vitamin B12 and iron may result in anemia and other health complications if not properly addressed [24].

A well-planned vegan diet can meet most nutritional requirements; however, particular attention must be given to nutrients such as protein, vitamin B12, vitamin D, calcium, iron, zinc, and omega-3 fatty acids due to potential risks of inadequacy and lower bioavailability [25].

The increasing demand for plant-based milk alternatives (PBMAs), defined as liquid products derived from cereals, legumes, nuts, and seeds, reflects their role as substitutes for conventional dairy milk [26]. Advancements in processing techniques and fortification approaches have improved their nutritional composition and sensory acceptability, enabling these products to serve as viable dietary alternatives rather than merely conventional beverages [27]. However, non-fortified plant-based dairy alternatives are poor sources of calcium, iron, and zinc, limiting their efficacy as nutritional substitutes in the absence of fortification. Although contaminant levels in commercial products remain low, elevated cadmium concentrations in certain home-prepared plant-based dairy alternatives underscore the importance of fortified alternatives and dietary diversification to ensure micronutrient adequacy in vegan populations [28].

Plant-based foods generally exhibit lower nutrient bioavailability due to a complex food matrix rich in dietary fibre and antinutritional factors, which limit digestive access and nutrient release. Although efforts have focused on matching protein quantity, plant proteins often demonstrate lower digestibility, essential amino acid availability, and bioactive peptide content compared to animal-derived proteins [29]. Moreover, while mean vitamin B12 intake appears comparable across dietary patterns, biomarker data indicate variations in nutrient status. For example, plasma vitamin B12 levels have been reported to be slightly higher plasma B2 levels in meat-eaters (92.0 nmol/L) compared to vegetarians (82.4 nmol/L) and vegans (79.8 nmol/L), with deficiency prevalence of 33%, 12.5%, and 10%, respectively [30]. Therefore, while vegan diets offer significant health advantages, optimizing nutrient bioavailability through appropriate food choices, preparation methods, and fortification strategies is essential to ensure nutritional adequacy.

Ultra-Processed Vegan Foods and Health Implications

Unhealthy plant-based diets often contain a high proportion of ultra-processed foods (UPFs), which may contribute to adverse health effects. UPFs are industrial formulations, produced through multiple processing steps to enhance shelf-life, palatability, and convenience [31]. Despite being perceived as healthier alternatives, these vegan ultra-processed foods differ substantially in nutritional and health attributes from animal-source foods, raising concerns about their long-term health impacts and suitability as true substitutes [32]. Plant-based milks and meat analogs, largely classified as ultra-processed foods, exhibit heterogeneous nutritional profiles and health effects, with some evidence suggesting cardiometabolic benefits compared to animal-based counterparts despite lower protein quality and variable micronutrient content [33]. Plant based food products were categorized into three groups:

(1) meat alternatives (e.g., plant-based burgers, sausages, nuggets, and tofu);

(2) dairy alternatives (e.g., beverages, yogurts, and cheeses derived from soy, coconut, rice, or almond); and

(3) composite products containing these alternatives, such as plant-based desserts and ready meals [34].

A summary of commonly reported ultra-processed vegan food products and their key characteristics, based on recent scientific literature, is presented in Table 1, highlighting the diversity and complexity of these products within modern plant-based food systems.

Table 1: Types of Ultra-Processed Vegan Food Products Reported in Scientific Literature

Product	Description	Reference
Dairy alternatives (plant milk)	Plant-based beverages produced from sources such as cereals, legumes, and nuts, designed to serve as substitutes for conventional milk	[35]
Vegan cheese	Plant-based cheese made from nuts, soy, or starch	[36]
Plant-based sausages	Vegan sausages made from textured vegetable protein and legumes.	[37]
Nuggets and cutlets	Breaded and processed vegan protein products	[38]
Plant-based burgers	Soy-, pea-, and wheat-based burger patties designed to mimic meat texture and flavour	[39]
Ready-to-eat vegan meals	Pre-cooked plant-based meals and convenience foods	[40]

As shown in Table 1, a significant proportion of widely consumed vegan alternatives fall under the category of ultra-processed foods, with considerable variability in their nutritional composition, particularly in terms of protein quality, sodium content, and micronutrient fortification. A study conducted by Maganinho *et al.* (2024) highlighted that dairy alternatives constituted 55% of products (64.4% beverages), while 86% of meat analogues were ultra-processed, showing lower saturated fat and higher fiber but variable protein and often high salt content, highlighting mixed nutritional implications [41].

Advancements in food technology have significantly contributed to the development of plant-based alternatives, with increasing emphasis on replicating the texture and flavor of animal meat using novel ingredients and innovative technologies [42]. The incorporation of novel protein sources, such as algae and mycoprotein, has shown potential to enhance both nutritional quality and sensory characteristics. In addition, emerging technologies, including three-dimensional (3D) food printing, are enabling greater product customization and innovation [43]. Techniques such as extrusion and fat structuring are further being optimized to improve texture, functionality, and overall product quality [44]. However, despite advances in processing, challenges in scalability, variability, and consumer acceptance persist, and future efforts must not only optimize production and sustainability but also reduce the nutritional and health concerns associated with ultra-processed foods (UPFs) [45].

Health Outcomes

A study conducted by Satija *et al.* (2016) found that healthful plant-based diet (hPDI)—rich in fiber, antioxidants, unsaturated fats, and micronutrients—was strongly associated with a lower risk of Type 2 diabetes (T2D), independent of BMI, whereas an unhealthful plant-based diet (uPDI) increased T2D risk due to higher glycemic load, added sugars, and lower nutrient quality. These findings highlight that diet quality, not just plant-based intake, is critical for T2D prevention [46]. In another study, a 16-week randomized trial showed that a low-fat vegan diet significantly improved diet quality (AHEI-2010), increased plant food intake (especially legumes), and reduced animal and fat intake, leading to weight loss, reduced fat mass, and improved insulin sensitivity. The study concluded that higher legume intake emerged as the strongest predictor of weight loss, highlighting the role of low-fat plant foods in improving metabolic health [47].

Despite the potential benefits of vegan and vegetarian diets, their effects on neurological health remain a growing concern, as the nervous system depends on certain nutrients that may be limited or less bioavailable in these diets. For example, vitamin B12—primarily obtained from animal-derived foods—is essential for myelin synthesis and neurotransmitter production, and its deficiency is associated with neurodegenerative disorders, cognitive decline, and neuropathy [48]. Similarly, omega-3 fatty acids—particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA)—are essential for maintaining neuronal membrane fluidity and synaptic plasticity; however, these are limited in vegan diets, as plant-based sources primarily provide alpha-linolenic acid (ALA), which has a low conversion efficiency to EPA and DHA [49]. Mitigation strategies include soaking/sprouting, proper cooking, vitamin C pairing, supplementation (B12, DHA/EPA), and fortified foods to enhance nutrient bioavailability and minimize antinutrient-related neurological risks in plant-based diets [50]. Strict vegan diets during pregnancy may increase the risk of small-for-gestational-age infants, lower birth weight, and nutrient deficiencies (e.g., B12, DHA), which can adversely affect foetal development. Careful nutritional planning, supplementation, and use of fortified foods are therefore essential to ensure optimal maternal and infant health outcomes [51].

As illustrated in Figure 1, healthy plant-based diets exert cardiometabolic benefits through multiple interrelated mechanisms. These diets are characterized by lower intake of saturated and trans fats and higher consumption of dietary fibre, plant sterols, vitamins, minerals, and phytochemicals, which collectively contribute to improved lipid profiles (↓LDL, ↓VLDL), reduced glycaemic index, and enhanced gut microbiota activity with increased short-chain fatty acid (SCFA) production. These changes lead to reduced central adiposity, improved insulin sensitivity, and attenuation of systemic inflammation, as reflected by decreases in markers such as HbA1c and inflammatory pathways. Furthermore, plant-based diets are associated with lower levels of L-carnitine and choline, resulting in reduced trimethylamine N-oxide (TMAO) formation via gut microbiota, thereby lowering oxidative stress, platelet activation, and blood pressure. These combined effects contribute to a decreased risk of chronic conditions, including fatty liver disease, nephropathy, and ultimately major cardiovascular outcomes such as coronary heart disease, stroke, and vascular dementia. These mechanistic pathways support findings from the systematic review by Jurek *et al.* (2025), which highlighted that vegan diets show promising cardiometabolic benefits in individuals with metabolic disorders, likely mediated through fibre, polyphenols, and gut microbiota modulation; however, evidence is limited by short study durations and predominantly Western populations [52]. Vegan diets achieve this by reducing gut dysbiosis, inflammation, and endothelial dysfunction, thereby lowering cardiovascular disease risk [53]. Overall, while vegan diets offer significant cardiometabolic advantages, their health outcomes are highly dependent on dietary quality, nutrient adequacy, and appropriate planning across different life stages.

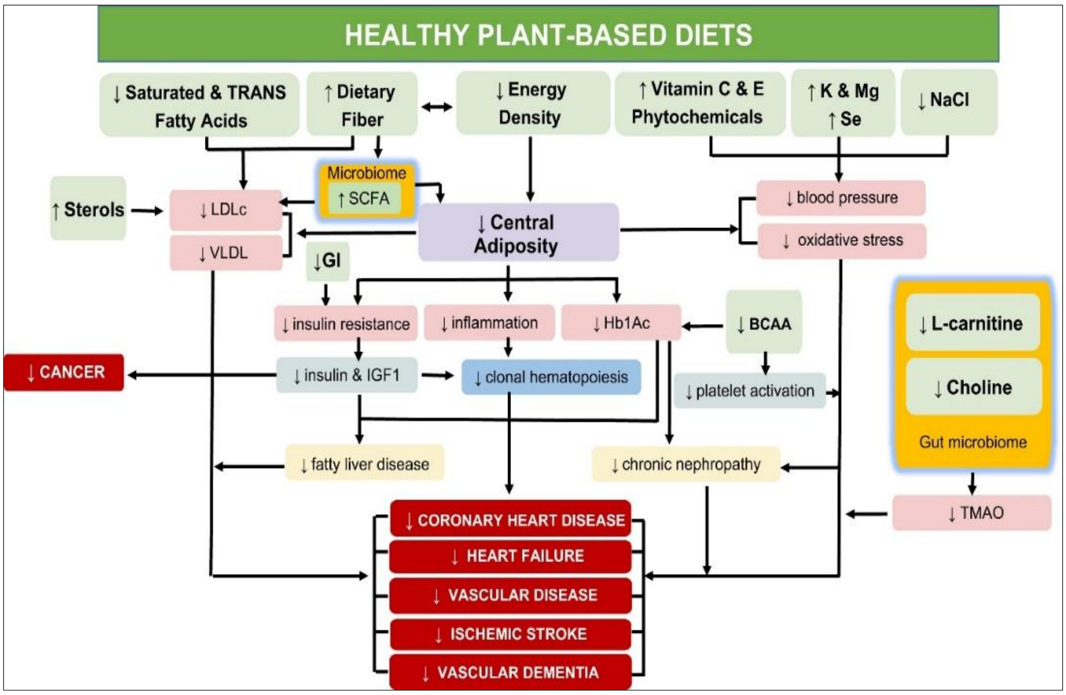

Fig 1: Cardioprotective mechanisms of healthy vegetarian diets [54]

Sustainability and Environmental Dimensions of Vegan Diets

Vegan and vegetarian diets, centred predominantly on plant-based foods, are widely regarded as some of the most environmentally sustainable dietary patterns [55]. A study conducted by Góralska-Walczak *et al.* (2024) found that ethical concerns, particularly animal welfare, were the primary drivers for adopting vegan and vegetarian diets over environmental motives. Compared to meat-based diets, vegetarian and vegan diets showed markedly lower environmental impacts—carbon footprint reduced by 47.0% and 64.4%, land use by 32.2% and 60.9%, and water use by 37.1% and 62.9%, respectively. These findings highlight the sustainability potential of plant-based diets, though further large-scale research is needed to refine environmental impact assessments [56].

Multiple large-scale assessments further reinforce the environmental advantages of plant-based dietary patterns.

For instance, Joseph Poore and Thomas Nemecek (2018) conducted a comprehensive global analysis and reported that shifting from animal-based to plant-based diets could reduce food-related greenhouse gas emissions by up to 49% while also significantly lowering land and water use [57]. Similarly, Marco Springmann *et al.* (2018) demonstrated that widespread adoption of vegan diets could reduce global food-related emissions by approximately 70% and contribute to reduced premature mortality [58]. Furthermore, replacing animal-source foods with plant-based alternatives can substantially decrease environmental pressures, particularly in terms of land occupation and biodiversity loss [59]. Collectively, these studies highlight that transitioning towards plant-based diets is not only beneficial for individual health but also represents a critical strategy for mitigating climate change and enhancing the sustainability of global food systems.

Figure 2 illustrates greenhouse gas emissions (t CO_2 eq. per person per year) associated with different food groups across three nutritionally comparable 2000 kcal diets – Conventional diet, Vegetarian diet and Vegan Diet. While nutrition remains relatively constant, total emissions are significantly higher with meat and dairy consumption.

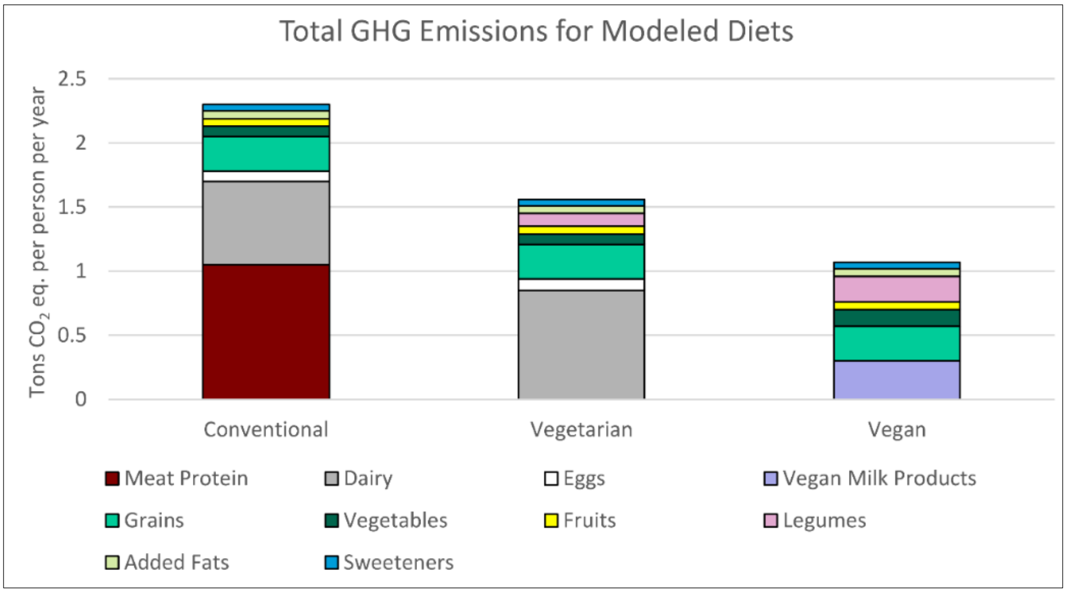

Fig 2: Greenhouse Gas Emissions Across Food Groups in Different Diets [60]

Impact of Vegan Diets on Carbon Footprinting

Carbon footprint (CF) refers to the total greenhouse gas emissions, expressed as CO_2 equivalents, generated directly and indirectly by an activity, product, or system across its life cycle [61]. Food systems contribute substantially to global greenhouse gas emissions (GHGEs), with red meat production alone accounting for approximately 23% of agricultural greenhouse gas emissions (GHGEs). The primary gases involved include nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2). These emissions contribute to land-use changes, particularly deforestation, and are projected to rise further in the future [62].

A significant proportion of greenhouse gas emissions (GHGEs) occurs along the food supply chain before final consumption. Meat production, in particular, generates substantially higher emissions compared to vegan and lacto-ovo vegetarian (LOV) diets [63]. Supporting this, a study by Choręziak and Rzymski, reported a progressive decline in carbon footprint with reduced animal-product consumption, with vegans having the lowest emissions (1.38 kg CO_2 eq/day) compared to vegetarians, fish-eaters, and meat-eaters. Per 1000 kcal, meat-based diets generate up to 94% higher emissions than vegan diets, with major contributors being cheese, fish/seafood, and meat in respective dietary groups [64].

Livestock production is a major source of methane emissions, with each cow emitting approximately 154–264 pounds of methane annually, contributing to a global release of at least 231 billion pounds of methane from the 1.5 billion cattle raised for meat production. Consequently, the environmental impacts of agricultural practices—particularly livestock production and meat consumption—are increasingly becoming a major concern for policymakers, especially in developing countries [65]. Evidence consistently shows that plant-based diets—particularly vegan diets—have the lowest environmental impact, with significantly reduced greenhouse gas emissions, land use, and water demand compared to meat-rich diets. However, the sustainability benefits depend on food choices within the diet, as higher consumption of processed plant-based or dairy alternatives can increase environmental footprints [66].

Conclusion

Vegan diets offer potential health and environmental benefits, including improved cardiometabolic outcomes and lower carbon footprints. However, these benefits depend on diet quality rather than the exclusion of animal products alone. Key concerns include the adequacy and bioavailability of nutrients such as vitamin B12, iron, and omega-3 fatty acids, as well as the rising intake of ultra-processed vegan foods. With proper planning, including diverse whole foods, fortified products, and supplementation, vegan diets can be nutritionally adequate and sustainable. Greater emphasis on whole, minimally processed foods and informed dietary choices is essential to maximize benefits while minimizing potential risks. Continued research and innovation are needed to enhance nutrient availability and support long-term health outcomes.

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