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Critical Review

Evaluation of Protein Adequacy From Plant-Based Dietary Scenarios in Simulation Studies: A Narrative Review

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ABSTRACT

Although a diet high in plant foods can provide beneficial nutritional outcomes, unbalanced and restrictive plant-based diets may cause nutrient deficiencies. Protein intake from these diets is widely discussed, but the comparison of animal and plant proteins often disregards amino acid composition and digestibility as measurements of protein quality. Poor provision of high-quality protein may result in adverse outcomes, especially for individuals with increased nutrient requirements. Several dietary modeling studies have examined protein adequacy when animal-sourced proteins are replaced with traditional and novel plant proteins, but no review consolidating these findings are available. This narrative review aimed to summarize the approaches of modeling studies for protein intake and protein quality when animal-sourced proteins are replaced with plant foods in diet simulations and examine how these factors vary across age groups. A total of 23 studies using dietary models to predict protein contribution from plant proteins were consolidated and categorized into the following themes—protein intake, protein quality, novel plant-based alternatives, and plant-based diets in special populations. Protein intake from plant-based diet simulations was lower than from diets with animal-sourced foods but met country-specific nutrient requirements. However, protein adequacy from some plant-sourced foods were not met for simulated diets of children and older adults. Reduced amino acid adequacy was observed with increasing intake of plant foods in some scenarios. Protein adequacy was generally dependent on the choice of substitution with legumes, nuts, and seeds providing greater protein intake and quality than cereals. Complete replacement of animal to plant-sourced foods reduced protein adequacy when compared with baseline diets and partial replacements.

Keywords: plant-based diets, protein quality, dietary modeling

Introduction

The transition toward a diet low in red meat and milk, and a higher intake of plant proteins from both traditional and novel sources may promote environmental sustainability through the reduction of greenhouse gas emissions [1–3], global water consumption, and land use [2], although these need to be confirmed by research. Alongside these, various health benefits may potentially be conferred by a plant-based (PB) eating pattern [4–6] although this also needs further verification. These include reduced risks of mortality from cardiovascular diseases and some cancers [6–8]. Taken together, recommendations to shift toward PB proteins may provide solutions to feeding the world population a healthier diet while maintaining planetary health [3,9–11].

However, such conclusions may be grossly oversimplified when all environmental parameters and trade-offs of nutrient sufficiency in life cycle assessments are examined. Even studies that have included nutritional science in environmental life cycle assessments have often used simplified functional units of nutrition without accounting for more detailed metrics such as nutrient bioavailability [12]. In the comparison of protein adequacy between animal and plant proteins, disregarding amino acid (AA) composition, digestibility and absorption as measurements of protein quality would provide little meaning in establishing the nutritional value of the protein source [12]. In support, studies have shown that the relative environmental footprint of animal-sourced to plant-sourced foods is substantially reduced when adjusting for protein quality [13,14].

Abbreviations: AA, amino acid; ASF, animal-sourced food; ASP, animal-sourced protein; DIAAS, digestible indispensable amino acid score; EAR, estimated average requirement; HEI, healthy eating index; IAA, indispensable amino acid; LNS, legumes, nuts, and seeds; NRF, nutrient rich food; PB, plant-based; PBA, plant-based alternative; PBMA, plant-based meat alternative; PSP, plant-sourced protein; RDA, Recommended Dietary Allowance; SFA, saturated fatty acid.

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Although diets limiting or excluding animal-sourced foods, such as vegan diets, may be plausible approaches for maintaining planetary health, research has shown that including small quantities of animal-sourced foods (ASFs) produced from sustainable feed production systems (eg, low-opportunity cost feedstuff) has the potential to feed global population with minimal land use and provide at least 9–23 g of high-quality protein in the daily diet [15]. By contrast, more environmental resources and higher intake of plant foods are required to attain the same nutritional outputs (eg, meeting total indispensable AA requirements) as animal foods [16].

Owing to the exclusion of all ASFs [17–19], a vegan diet is associated with increased risks of nutrient deficiencies [7,17,20,21], particularly in more vulnerable population groups—infants, children, adolescents, pregnant and lactating females, and the elderly [22,23]. Particular attention needs to be paid to suboptimal intake or poorer bioavailability of nutrients such as protein. Although plant-sourced proteins (PSPs) contain all 9 indispensable amino acids (IAAs), these are distributed in more varied or lower quantities than animal-sourced proteins (ASPs) [24–26], hence being comparatively inferior in quality. In addition, digestibility and nutritional availability of IAAs from plant proteins are affected by processing conditions in the production of novel and ultraprocessed [27] foods and meat alternatives [26,28].

Nutritional and health outcomes arising from the switch to a vegetarian or vegan diet are highly dependent on the type of food used as the substitution [29]. The healthfulness of plant-based alternatives (PBAs) in the current market varies according to the formulation of their ingredients. However, insufficient empirical evidence from randomized clinical trials [30,31] leaves questions about the long-term health impacts of regular PBA consumption [32] unanswered, especially when whole plant foods are concomitantly reduced [26]. Increased consumer acceptability of meat and dairy alternatives are evidenced by higher purchasing data from Asia, the United Kingdom, and the United States, which may be motivated by marketing strategies aligned with health, environmental, and animal-welfare promotion [30,33]. However, terminologies such as PB burgers, nuggets, and sausages [34] may tend toward junk food consumption with unhealthy condiments, sides, and beverages. These conflict with health messages associated with a whole-food PB diet. Nevertheless, the value of alternatives to a PB diet must not be neglected. Other than adding taste and variety to an individual's diet, they may provide time-efficient and convenient sources of nutrients, especially if they are enriched with bioavailable proteins, and provide sources of dietary fiber and bioavailable micronutrients [30,35].

Simulation studies examining results from dietary scenarios that replace ASFs with plant-sourced alternatives may serve as efficient, safe, and inexpensive predictions of challenges associated with this dietary transition [31,36]. Hypothesized results can subsequently inform further research, nutrition recommendations, dietary, and health practices [37]. Selecting a diet that meets goals in nutrition, health, affordability, and sustainability is an ongoing challenge [38,39]. Owing to the variability in the nutrient composition [40] of PBAs, the present and future assessment of their nutritional outcomes are challenging [30,31]. Although there have been several systematic reviews conducted on the outcomes of PB diets [5,41], there are no reviews that outlined the hypothesized outcomes of protein adequacy in PB dietary models.

The first aim of this narrative review was to compile and summarize the approaches of modeling studies that have examined the nutritional impacts of PB dietary patterns, primarily for protein adequacy and protein quality. The second aim was to examine how protein intake and AA composition will vary with inclusion of PBAs in the diet. Finally, the review aimed to examine the nutritional outcomes for protein across age groups when animal protein is replaced by plant protein. To our knowledge, this is the first review that has examined the protein adequacy of PB dietary patterns from dietary models.

Methods

Overview of Review Process

This narrative review is informed by proposed frameworks from literature [2,42,43] as illustrated by Figure 1.

Relevant simulation studies were searched through recognized electronic databases—PubMed, Scopus, and Google Scholar. Studies from the year 2000 to present were selected to capture the most current representation of PB dietary patterns [44].

The search strategy was informed by keywords from past systematic and narrative reviews [2,44–46]. Search terms entered were "plant-based diet" OR "plant-forward" OR "vegan diets" OR, "vegetarian diets" AND "simulation" OR "modelling" OR "dietary model." To attain results for simulation studies with novel proteins, the following search terms [30,47,48], "simulation" OR "modelling" AND "plant-based meat alternatives" OR "PBMA" OR "plant-based proteins" OR "plant-based meat" OR "plant-based meat analogue" OR "plant-based substitute" OR "alternative proteins" OR "dairy alternatives" OR "plant-based milk" OR "plant-based beverages" were entered. To attain saturation, additional references were identified by manual search through the reference lists from the retrieved articles. Connected Papers (www.connectedpapers.com) was used to track and achieve coverage of relevant studies. Duplicated studies that were common across databases were removed. The search was limited to peer-reviewed articles available in full-text and in English.

Inclusion and Exclusion Criteria

The widespread use of the term PB diet results in varied definitions, from the complete exclusion of all animal foods [17–19], to the inclusion of limited quantities of fish, meat, poultry, dairy, and eggs amidst a larger intake of plant foods [49–52]. This review defines PB dietary models as those that replace animal-sourced proteins with varied quantities of plant-sourced foods and a 100% replacement that simulates a vegan diet. To include all nutritional outcomes arising from varying quantities of animal protein to plant protein substitution, studies that examined flexitarian or pescatarian diets were also analyzed as types of PB diets. Studies that have not used simulated or computational dietary models were excluded. Studies that did not examine protein intake were excluded.

Results

A total of 23 studies were included in this review. Baseline diets were based on dietary recalls and food composition data

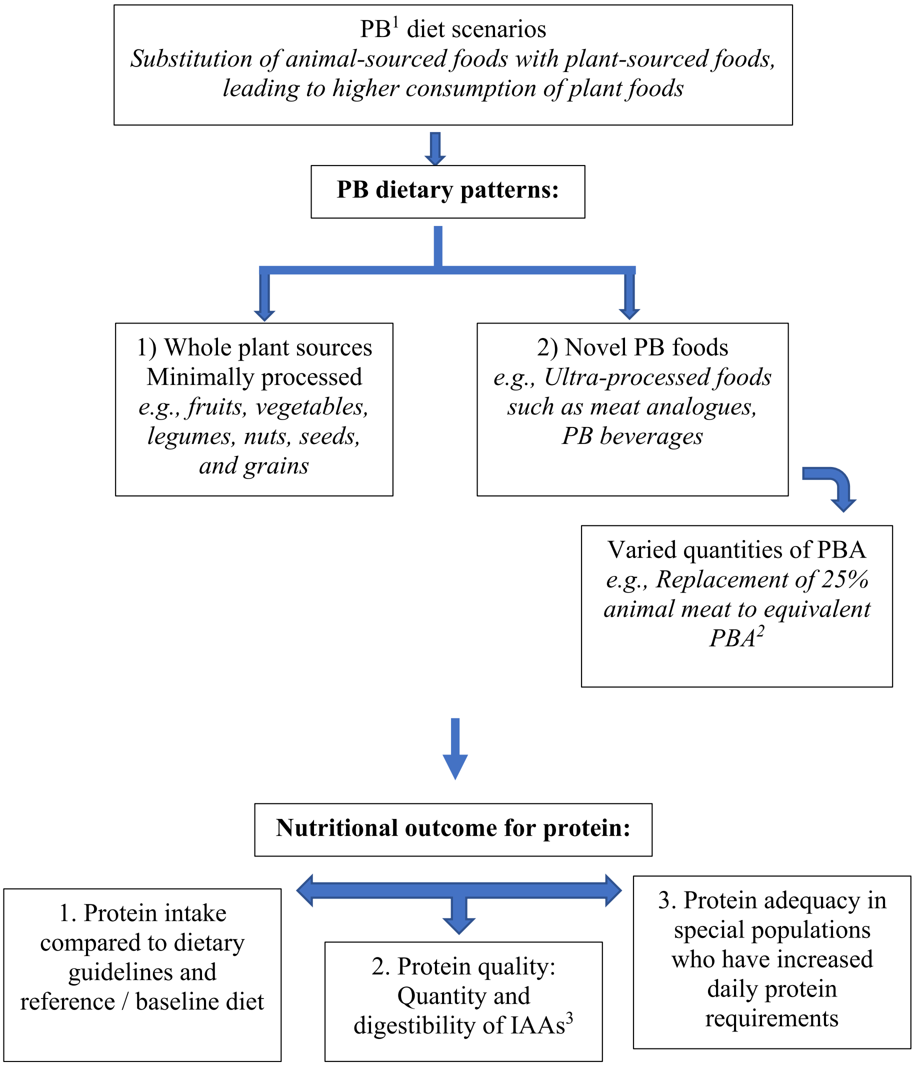

FIGURE 1. Framework of analysis. PB, plant-based; PBA, plant-based alternative; IAA, indispensable amino acids.

sets of populations predominantly from high-income Western countries. Protein content from plant-sourced foods was commonly examined among the studies (Table 1) Four studies included diet quality indices to evaluate the nutrient quality of modeled diets (Table 2). Only 4 studies examined protein quality, using protein digestibility scores (Table 3). Five studies included the protein intake from novel PBAs (Table 4) . Six studies analyzed nutritional outcomes in scenarios involving special populations, and 3 are presented in Table 5

Methods used were heterogeneous across studies, but most substitutions of protein sources were based on gram-for-gram replacement of ASFs with PB protein sources [29,31,53–56,58,59,63–67]. This may not account for higher rates of carbohydrates, fat, dietary fiber, and thus, higher caloric density per unit of protein mass [68] in different foods. A more accurate substitution was used by 2 studies, which replaced an equivalent mass of protein or AAs from ASFs [60,62]. Only 1 study examined isocaloric substitutions in an energy-adjusted model [60]. In an isocaloric comparison, PB protein sources generally provide poorer protein quality than ASFs. Therefore, such a method is limited in practicality as increased caloric intake of PSFs is needed to achieve the same quantity of AAs as provided by ASFs [69].

Protein Intake in PB-Simulated Diets

Lower protein intake was observed in most dietary scenarios when animal proteins were substituted with plant proteins but were still above country-specific nutrient reference values or the protein content of reference diets (Table 1). Similarly, in an evaluation of protein intake from vegetarian diets among western populations, a low prevalence of vegetarian individuals were consuming below the Recommended Dietary Allowance (RDA) of 0.8 g/kg/body weight despite a lower protein contribution to energy intake than that of those consuming omnivorous diets [24].

In a few other studies, protein deficiencies were observed in scenarios where ASFs were completely replaced with plant foods. In 3 separate studies on United States populations, which used similar methodologies, a decrease in protein intake for all age groups was observed, with an increase in the proportion of population below the estimated average requirement (EAR) [64–66]. In PB dietary scenarios from Australia, the complete

TABLE 1
Dietary models assessing protein intake.

Reference	Study aim and target population	Simulation design	Protein assessment
53	Examine the large-scale consequences in the EU when replacing ASFs with PB foods	25% or 50% decrease in meat, poultry, eggs, and dairy, compensated by higher intake of cereals and pulses	Alternative diet resulted in 10% lower protein intake than reference diet, but mean protein intake is still at least 50% higher than dietary requirements
54	Examine effect on nutrient intake when shifting toward more PB diets for the Dutch adult population, when compared with current diet	1. Less meat and dairy scenario: Replacement of 30% meat and dairy products with PB alternatives 2. No meat and dairy scenario: replacement of 100% of meat and dairy	For 100% replacement, protein intake decreased by 21 g/d for males and 15 g/d for females, but percentage below EAR is 3% for females and 1% for males. For less intake, lower protein intake found but not significantly different to current diet
67	Explore the role of grain legumes in Swedish adults	50% reduction in meat and replaced by 55 g equivalent of cooked grain legumes	Protein intake in scenario is 6% lower than in current Swedish diet but still within Nordic nutrient recommendation for adults (30–64 y)
43	Develop an optimized diet for adult Italian population to meet national DRIs with minimum GHGE	Linear programming model to minimize GHGE while meeting (eg, lower, and upper bounds) protein intake, acceptability, and health constraints	Total protein intake of optimized diet is lower than observed diet (67 g/d compared with 76 g/d)
56	Determine nutritional adequacy of dairy-free and vegan diet in varied caloric intakes	Model 1 (dairyALT): Replace dairy with soy milk and fortified yogurt Model 2: Replace cup equivalent of dairy and eggs with PSPs	Decrease in protein by 10% to 20% in both models for 1800-kcal/d and 2000-kcal/d plans, within AMDR, and >100% meeting DRI for all models, all calorie levels, and both sexes
57	Assess carbon footprint of optimized vegan, vegetarian, and omnivorous menus for Italian school lunches	Two-wk schedule, adhering to Italian RDA with constraints set for protein intake	Weekly protein for all models above lower bound (100 g). Protein intake increases from vegan to vegetarian to omnivorous menus
23	Examine impact on average intakes in selected nutrients and changes to population shares below DRI when replacing meat with legumes	Model 1: <70 g/d red and processed meat Model 2: <50 g/d red and processed meat Model 3: <30 g/d red and processed meat	Decrease in absolute protein intake (%) was only evident in males for scenario 50 and 30 g and in females for scenario 30 g. No significant difference in absolute protein intake (%) between all models and reference diet

ALT, alternative; AMDR, acceptable macronutrient distribution range; ASF, animal-sourced food; DRI, dietary reference index; EAR, estimated average requirement; EU, European Union; GHGE, greenhouse gas emissions, PB, plant-based; PSP, plant-sourced proteins; RDA, Recommended Dietary Allowance.

replacement of meat and milk led to more undesirable changes in protein intake of more than 5% from baseline diet, for young children (2–3 y), adults (19–30 y), and older adults (71 y) [31]. It was unclear whether these changes were below nutrient reference values, but in scenarios with smaller amounts of replacements, nonsignificant decreases in protein intake were observed.

These results imply that completely transitioning to PB dietary patterns reduces protein intake and, potentially, incurs risks of deficiency when compared with country-specific nutrient reference values. A systematic review examining protein intake among 26 studies found that protein intake was the lowest in vegans [46], with 2 studies finding consumption to be below the recommended daily intake [70,71]. The European Prospective Investigation into Cancer and Nutrition Oxford similarly found higher incidences of inadequate protein intake with increasing intake of plant foods, with the highest prevalence observed among vegans [72]. However, more recent cross-sectional studies on vegans have however shown inconsistent results for protein and AA intake. A lower median intake of some IAAs by more than 30% was observed in German vegans than that in omnivore counterparts [73]. By contrast, a higher protein intake among 83 Norwegian vegans than vegetarians and pescatarians was observed and attributed to the inclusion of soy-based meat substitutes [74]. Challenges are evident in accurately identifying the prevalence of low protein intake among vegans owing to the variability in dietary intakes and individual protein requirements [24]. Current assessments of protein intake are further complicated with additions of novel PBAs, which have diverse ingredient and nutritional compositions.

Protein intake sufficiency from diets where only smaller proportions of animal protein were substituted is further supported by evidence from an Indonesian study [39]. Three increasingly PB diet scenarios (no-dairy diet, fish and poultry diet, and low food-chain diet) were designed to be culturally aligned and specific to the health concerns of the Indonesian population. Improved nutritional compositions were evident in these modeled diets, when compared with the current Indonesian diet, which provides excessive energy from rice and has poorer diet diversity and nutrient density [39]. Although lower protein intake was observed in these PB diets, it was not markedly different from the current diet. Most of the protein provided from the PB diet scenarios was from pulses, nuts, and seeds.

However, it is important to consider that protein intake adequacy was likely achievable in these scenarios because staples and protein-rich foods were adjusted to meet protein criteria, and the absolute quantity of protein was set to 69 g/d for an average individual, in alignment with dietary guidance of 10%–15% of energy from protein consumption per day [39,75]. However, plant-sourced foods have poorer protein quality owing to at least 1 limiting AA—lysine from grains and sulfur-containing AAs from legumes [76]. A single average score for IAAs was provided for the Indonesian scenarios, and a score of >100 showed that requirement for all IAAs was achieved for an average individual [39]. However, the accuracy of this summation remains unknown because AA profile and bioavailability differ among foods [77].

TABLE 2
Dietary models using diet quality measurements.

Reference	Study aim and target population	Simulation design	Protein assessment
58	Effects of increasing plant proteins with decreasing processed meat in Canadians 1 year and above	Increase currently consumed plant proteins from legumes, nuts, and seeds by 100% while halving red and processed meat consumption	At baseline, plant foods contributed lower protein than red and processed meat Doubling consumption of PBMAs^8 and halving intake of red and processed meat led to significant decrease in protein: 78 ± 0.6 to 73 ± 0.6 g/d ($P < .05$) 3. Higher NRF score in modeled diet (517–526; $P < .05$)
59	Test nutritional adequacy and diet quality of ovovegetarian and vegan diet models in Americans	5-day menus for ovovegetarian and vegan diet of 2000 kcal	Protein was 15% (AMDR 10%–35%) for vegan and 16% for ovovegetarian. Average intake of protein was 74 g/d for ovovegetarian and 72 g for vegan. Perfect HEI-2015 scores (100%) for protein intake
40	Impact of optimized meat substitute, made of pulses and minimally processed ingredients on French adults	One optimized meat substitute and 43 existing meat substitutes with constraints set for nutritional, technological, and interindividual variability	Six-point increase in PANDiet score in replacing meat with optimized meat substitute A quarter of meat substitute increased PANDiet score above value in observed diet. Protein unchanged between all modeled and reference diets
36	Simulate meal plans with different levels of animal protein reduction in United States adults (31–50 y) and assess diet quality	MILP to create 100 7-d meal plans (breakfast, lunch, dinner, snack) for United States reference diet, vegetarian, pescatarian, flexitarian diets of 25%, 50%, and 75%	Highest animal protein foods found in United States reference diet, higher meat, and poultry intake for males than females in all models. More contribution of egg protein in pescatarian and vegetarian models for both sexes. Highest contribution of protein from seafood in pescatarian model 4. Highest contribution of protein from dairy in vegetarian and pescatarian models

AMDR, acceptable macronutrient distribution range; HEI, healthy eating index; MILP, mixed integer linear programming; NRF, nutrient rich food; PANDiet, probability of adequate nutrient intake; PBMA, plant-based meat alternative.

Nutrition outcomes from dietary models are dependent on the reference diets used as the comparison. Another study found a meaningful decrease in protein intake when there was a 30-g and 50-g substitution of meat to legume intake only in males and not in females [23]. This could be attributed to higher baseline intake of meat among males than that in females, so smaller decreases in meat intake would result in greater decreases in protein intake [23]. In a dairy-free vegetarian and vegan dietary model for United States males and females (aged 19 y or older), soy milk, soy products, and fortified soy milk were food items chosen, but these were not preferred milk alternatives among United States individuals [62]. These scenarios show that interpreted nutrient outcomes may not represent the population's diet [62] and deviate from the habitual intake.

Diet quality indices are often used to measure the healthiness of PB dietary patterns [78] and were used in some models (Table 2). One example is the Healthy Eating Index Score-2015 (HEI-2015), which was used to determine the diet quality of an ovovegetarian and vegan diet when compared with that of a healthy vegetarian dietary pattern for healthy United States adults [59]. The HEI is a 100-point metric system that measures the adherence of these diets to the Dietary Guidelines of Americans (DGA) [36,79]. A HEI-2015 score of 100% was attained for protein intake, and protein was within the acceptable macronutrient distribution range (AMDR) (10%–35%) in both ovovegetarian (16%) and vegan diets (15%) [59]. Similarly, another study on United States adults analyzing PB diets using the HEI-2015 showed higher HEI scores with decreased intake of animal protein, with the highest HEI score from vegetarian diets [36].

However, HEI as a diet quality metric favors seafood, plant protein, dairy and foods elevated in unsaturated fatty acids and penalizes saturated fatty acids (SFAs), added sugars, and sodium [36]. It should not be seen as a tool for solely assessing the protein adequacy of diets. Furthermore, plant proteins and seafood were combined as one group for analysis, when a vegan or vegetarian diet should not contain any seafood [59].

Although protein intake decreased in PB diet scenarios for a Canadian population, scores for the nutrient rich food (NRF) index increased [58] (Table 2). NRF scores are calculated with similar beneficial and detrimental nutrient patterns to HEI [58]. These indices may provide a gauge on the overall quality of diets based on the summation of composite nutrients but provide less information about the contributing weightings and bioavailability of each nutrient toward the overall nutritional value of food [80].

Possibly, owing to the varied scope and focus of these studies, few have accounted for AA composition in their analysis. Hence, the bioavailability of protein in the abovementioned PB scenarios have not been examined. Therefore, consideration of protein quality in PB diets is of greater importance than accounting for protein intake alone in populations that are generally not limited in gross protein intake.

Protein Quality in PB-Simulated Diets

Protein quality measurements consider the quantity and composition of IAAs in the protein source and the digestibility and physiologic utilization of each AA [14,69,76,81]. PSPs are often considered to have lower quality than ASPs, owing to lower

TABLE 3
Dietary models evaluating protein quality.

Reference	Study aim and target population	Simulation design	Protein assessment
60	Assess sufficiency for protein and lysine in association with varying plant:animal protein intake, achieved with different methods of replacing animal with plant foods, for French adults	Model P: Replacement with same quantity Model A: Replacement with same energy from habitually consumed plant foods Model B: 100 % isocaloric replacement with legumes, nuts, and seeds Intermediate models adjusting proportion of high-protein plant foods and animal proteins: 0%–100% (eg, C_{20} implies 20% plant, 80% animal)	Protein and amino acid intake met population requirements. Adequate intake up till 50% of plant protein intake; lysine became limiting above 70% of plant protein intake. Replacement with legumes, nuts, and seeds allowed adequate intake for higher proportions of plant intake
61	Assess impact of nutrient bioavailability in 3 modeled sustainable diets, in French adults	Diet optimization departing least from observed diet	Food composition not altered when protein bioavailability was accounted. Protein was never limiting in both males and females Overall protein digestibility: 95% for both males and females; AA score was 1.3; total protein was 117% for females and 122% for males; PDCAAS was 112% for females and 116% for males
39	Determine how alternative dietary scenarios compare with current food patterns in Indonesia, for nutrient content, contribution to climate change and cost	1) No-dairy diet 2) Fish and poultry diet 3) Low food-chain diet Above diets achieved achieve same energy and protein requirement as current diet 4) EAT-Lancet diet 5) Optimized to individual nutrient needs within a household 6) Current diet	Optimized diets: a) met requirements for all nutrients and IAA b) higher proportion of animal-sourced foods for growing children, and adult males c) higher cost and higher GHGE diets for adolescent girls and lactating females owing to higher animal-source foods
62	Assess protein sources, intake, quality and cost across quartiles of protein intake for United States adults (19 y or older) 2. Model effects of replacing AA from grain protein sources with nongrain plant proteins across quartiles	1. Increasing quartiles and defined levels of protein intake 2. Replacing 25% and 50% of AAs from grains with equivalent amount from legumes, lentils, and other nongrain plant proteins	1. IAA score and PDCAAS were lower across increasing quartiles ($P_{\text{quartile trend}} < 0.05$). 2. Total protein intake, IAA score, and PDCAAS lower in higher defined levels than lower defined levels 3. Effect of replacing AAs for legumes and lentils: quartiles 3 and 4 had greatest improvements in IAA and PDCAAS scores 4. Absence of protein complementation led to 25% decrease in PDCAAS of diets from lowest to highest defined level

AA, amino acid; GHGE, greenhouse gas emission; IAA, indispensable amino acid; PDCAAS, protein digestibility corrected amino acid score.

quantity of some IAAs, which are further impeded in digestion by antinutritional factors [14,26,82]. This is indicated by generally low digestible indispensable amino acid scores (DIAAS) for plant foods; scores 100 and above indicate completely utilizable and higher quality protein [69]. To improve dietary protein quality in vegetarian diets, different protein sources with complementary IAA profiles can be combined in meals [25,82] or be consumed in higher quantities to increase amino acid uptake in plasma [83].

Few studies in this review have analyzed the quantity of IAAs in PB dietary scenarios [39,60–62] (Table 3). Three optimized French diets found that protein was never the limiting factor for either sex in all 3 models, even though total protein (% RDA) decreased in optimized diets lower in ASFs [61]. This was indicated with high scores for overall protein digestibility (%) and AA score. Instead, micronutrient content was the deciding factor in final diet composition.

Achieving lysine adequacy was a challenge with higher intake of plant foods [60]. For example, lysine inadequacy exceeded protein inadequacy when plant protein constituted >70% of protein intake [60]. Lysine contribution from habitually consumed cereal foods within the population is relatively poor [60,66,84]. Different outcomes were attained when animal foods were replaced with high-protein plant foods in the form of legumes, nuts, and seeds (LNS) [60]. Owing to their greater protein density than cereals, it would take higher mean plant protein contribution, in energy-adjusted intake to achieve a probability of protein inadequacy [60], hence allowing closer achievement of protein and AA adequacy. Such outcomes were not emulated in the United States studies [64–66] when LNS were used to replace animal foods owing to low consumption in the original diet. Further increments would have been unrealistic projections of dietary and energy intake and deviate greatly from the population's habitual diet [56,66].

In another United States study using the same population database [62], protein quality as measured by IAA score and the protein digestibility corrected amino acid score, calculated from intakes of each IAA per gram protein [85], generally decreased across increasing quartiles of plant protein intake. However, in models where 25% and 50% of AAs from grains were replaced with those from legumes, lentils, and nongrain plant protein, protein quality improved. These results thus corroborate conclusions that protein quality in PB diets improves when animal proteins are substituted with LNS rather than with grains [60].

TABLE 4
Dietary models evaluating protein contribution by PBAs.

Reference	Study aim and target population	Simulation design	Protein assessment
63	Evaluate nutritional implications of complete and partial meat replacements, and with different alternative products, as compared with current intake in UK population	Model 1: Replacement with 25%, 50%, 75%, and 100% in quantity Model 2: 100% replacement of meat with alternatives of varied ingredients (vegetable, mycoprotein, legume, tofu, nut, and soya) Model 3: 100% replacement with fortified and unfortified alternatives	Model 1: Graded decrease in protein with increasing substitution Model 2: Significant reduction of protein across all alternatives, but particularly from nut, vegetable, and legume Model 3: Fortification results in smaller projected reduction in total protein from current intakes
29	Assess how nutritional impact varies with different plant substitutes in a French adult population (18–79 y)	Model 1: Meat substitution with 56 PB alternatives Model 2: Milk substitution model with 16 PB alternatives Model 3: Dairy dessert substitution with 24 PB alternatives	Model 1: Significant increase in PANDiet score for soy-based and pulse-based substitutes but significant decrease with cereal-based substitutes. Model 2: Diet quality score for protein decreased with sweet PB milk, cereal, and nut-based milk Model 3: Diet quality score for protein improve with fortified and soy-based products and significant decrease in non–soy-based substitutes
55	Model impact of diets with less or no meat and dairy on nutrient intakes in Dutch children (2–6 y old) compared with reference diet	Model 1: 30% replacement Model 2: No meat and dairy	Model 1: 3% decrease in total protein intake but 0% of population consuming below EAR levels Model 2: 8% decrease in total protein intake but 0% of population consuming below EAR levels
34	Determine whether replacement of animal products with novel PBMA and dairy alternatives will lead to equivalent nutrient intakes when compared with standard omnivorous diet in a US population	Flexitarian, vegetarian, and vegan diets where animal foods were substituted with whole plant foods (traditional) or with PBMAs, coconut-based or soy-based dairy alternatives (novel)	1. Similar protein intake in flexitarian, vegetarian, and vegan diets when compared with reference diet; protein intake met dietary guidelines for all diets. PBMAs and dairy alternatives were matched for protein intake with the other diets
31	Estimate nutritional implications of substituting animal-sourced meat and dairy milk with alternatives in Australian population of young children (2–3 y), adults (19–30 y) and older adults (71 y and older)	1. Total replacement: increase of “meat” by 42 g/person/d and “milk” by 1 L/person/d 2. Partial replacement: increase of “meat” by 6.5 g/person/d and “milk” by 6 g/person/d	1. Substantial decrease in protein intake for total replacement scenarios, of 8% for young children but not for other groups. Insignificant decrease for partial replacement scenarios 2. PB meat products have lower protein than beef 3. Predicted 2%–10% decrease in protein intake for total replacement scenarios for all populations

EAR, estimated average requirement; PB, plant-based; PANDiet, probability of adequate nutrient intake; PBMA, plant-based meat alternative.

Protein digestibility corrected amino acid score was used in some studies [61,62] as a protein quality metric. However, this may provide overestimations of protein quality because of several limitations highlighted widely in the literature, including the truncation of protein quality scores and determination of digestibility at the protein rather than IAA level [77,81,86]. Current methods in the simulation studies reviewed in this study [23,63–67] rarely account for protein quality in complementary sources of protein [76] but focused on comparison of protein adequacy in isolated foods, limiting representation of true protein quality from mixed diets. Biases are introduced in the selection of plant protein in each simulation model when plant foods have different AA profiles (eg, grains compared with soy or legumes). Combining plant proteins in a meal (eg, grains and lentils) can overcome the differing limiting AAs of each plant source and improve protein quality to be comparable with AA profile of animal proteins [76,82]. Future simulation studies should overcome this limitation by simulating mixed diet scenarios and accounting for overall protein quality measurements in mixed diet settings.

PBAs in Dietary Simulations

Considering the current addition of meat and dairy alternatives marketed to be sustainable and healthy, the nutritional value in alternative PB foods must be established. This is especially so if current formulations of PBAs are designed to simply emulate the appearance, texture, taste, and comparable protein content with meat, without considerations of protein quality and micronutrient content [40,87].

A comparison made between a reference United States omnivorous diet with 7 PB diets of varying restrictions on meat and dairy (Table 4) found lower protein contribution from PBAs [34]. Protein intake decreased in vegetarian and vegan modeled

TABLE 5

Dietary models evaluating protein requirement in special populations

Reference	Study aim and target population	Simulation design	Protein assessment
64	Determine nutrient intake and adequacy in children (2–18 y) and adults (19+ y old), with increasing plant foods or dairy, when compared with usual intake (baseline)	Model 1: 100% increase of currently consumed PB foods with corresponding decrease in animal foods Model 2: 100% increase of protein-rich plant-based foods (eg, legumes) with corresponding decrease in animal foods Model 3: Doubling currently consumed dairy products	Model 1 showed decrease in protein intake for all groups with 3× of 2 to 18 y below EAR, and 321% increase of 19+ y old below EAR. Model 2 showed no difference in meeting macronutrient intake and EAR in both groups, compared with baseline. Model 3 showed increased intake of energy, protein and SFA with decrease percentage of individuals in both groups below protein EAR
65	Determine energy and nutrient adequacy in adolescent girls (9–18 y old) with increasing plant foods or dairy, when compared with baseline	Identical models as Cifelli et al. [64]	Model 1 showed decrease in protein intake with 3× increase in percentage not meeting EAR for protein. Model 2 showed no differences in meeting macronutrients and EAR in both groups, compared with baseline. Model 3 showed increase in intake of energy, protein and SFA with decrease percentage of individuals in both groups below protein EAR
66	Determine protein intake in older Americans aged 51–70 y and older than 70 y, by increasing plant-based foods or dairy products, when compared with baseline	Identical models as Cifelli et al. [64]	Protein-rich plant foods were not a major component of the diet; dairy intake was half the recommended intake. Model 1 showed decrease of total protein intake and increase in percentage below EAR for both age groups and sexes, whereas model 2 showed no meaningful change in protein intake when compared with that in baseline for both age groups and sexes

EAR, estimated average requirement; SFA, saturated fatty acid.

diets, so the addition of high-protein snacks was required to meet protein requirements [34]. The study found inadvertent consequences of increasing energy and sodium intake resulting from the addition of ultraprocessed foods in novel PB diets, when compared with traditional flexitarian models where the inclusion of eggs and dairy did not lead to the same nutritional outcomes [34]. In the case of vegan cheese, coconut-based yogurts and ice cream, a higher intake of fat and lower intake of protein was observed [34]. However, no statistical approach was used in this study to determine whether nutritional differences between modeled diets were significant. The study did not make any associations between the compositions of each alternative with its protein contribution, whereas the type of ingredient used in each substitute was evaluated in the calculation of the diet quality (PANDiet) score of 3 dietary scenarios in French adults [29].

The PANDiet research showed that diet quality was dependent on the type of plant substitutes used. For example, scores increased significantly ($P < 0.0001$) when substitutions were soy-based products (+0.57), tofu, tempeh, or soy protein (+1.58) but decreased with PB sausages (−0.60) and cereal-based foods (−0.72) [29]. Similar improvements in diet quality were observed for milk and dairy substitutes that were derived from soy products [29]. For example, for dairy dessert substitutes, PANDiet scores significantly improved with soy-based substitutes (+0.06, $P < .0001$) and calcium-fortified plain PB desserts (+1.35, $P < 0.0001$) but decreased significantly for PB mousses (−2.85, $P < 0.0001$), and non–soy-based substitutes (−1.31, $P < 0.0001$) [29]. These findings indicate that protein content will vary depending on the ingredient used to formulate substitutes.

In a further evaluation, meat was substituted with an equivalent quantity of pulse-based replacement [40]. This meat replacement was then optimized to meet the nutritional constraints of French adults, used in one diet model and compared with other market-derived meat substitutes in 43 other diet models. The exclusion of soy products (tofu or textured soy protein) resulted in a lower protein content (8.5 g/100 g) than that in meat and other meat substitutes on the market.

Soy-based PBMAs are often formulated with processed soy products such as isolates, textured soy, and concentrates, which can provide for higher protein content and quality [88] if used in a meat substitute. Furthermore, soy is found to have the highest DIAAS score among plant proteins [25] and is a good source of lysine [89]. However, the digestibility and long-term health impact from these newly formulated soy products warrants further research, alongside acceptability in cultures where soy is not traditionally consumed.

Surveys on PBMAs in the Swedish market have found varied nutrition contribution for protein but no difference when compared with meat [90]. Once again, this variability may be dependent on the product composition [55]. Achieving similar digestibility to animal sources is possible if processed soy concentrates or isolates are used [77] but may be lower if other sources were used.

Further evidence was provided when examining the replacement of meat with different varieties and quantities of PB alternatives [63]. When compared with meat, the greatest projected decrease in protein intake was from the nut source (−19.79 g/d; $P \leq 0.001$), followed by vegetable (−19.33 g/d; $P \leq 0.001$), and then legume (−15.43 g/d; $P \leq 0.001$) [63]. Even tofu had a significant reduction of total daily protein intake (−4.87 g/d; $P \leq 0.001$) [63], but this reduction was smaller than the other alternatives, further supporting soy products as a better PB option for protein contribution. Because the models still included eggs and dairy, the loss of 20 g/d of protein was due to removal of meat from the diets, and this could result in dire consequences especially for more vulnerable age groups (very young and very aged) [63] in the absence of careful diet planning [91].

In a Canadian study to model the nutritional impacts of increasing PBMAs and decreasing red and processed meat intake, the NRF score was used to determine diet quality [58]. This metric measures the nutrition quality per serving [80] and significantly increased (517.4–525.8; $P < 0.05$) in the simulated diet. This suggests an improvement in nutritional value when reducing red and processed meats and increasing PBA. However, results from the model showed a significant reduction for protein (77.8 ± 0.6 g to 73.4 ± 0.6 g) when PBAs were doubled while red and processed meat was halved.

Although moderate replacements of red and processed meat with traditional plant proteins may confer improved nutritional and health outcomes, the same may not be true of PB substitutes, owing to higher quantity of sodium and sugars and poorer provision of protein from some types of substitutes [34,63,92,93]. However, these foods are higher in fiber, which is absent in meat [94]. PBAs' resemblance to the taste and texture of meat could aid high meat-eaters to transit toward including more plant foods into their diet.

The healthfulness of a PB diet is dependent on consumer choice in the selection, frequency, and quantity of both traditional and novel products. These factors lead to complexities in the pursuit of a balanced PB diet. Although nutritional risks may exist if diets contain a high proportion of these processed products [34], smaller quantities may not have the same impact, and this is essential to investigate. Few simulation studies have compared the implications of gradual increments or intake frequency of ultraprocessed PBAs in diets, and only 3 are represented in this review [31,55,63].

All 3 studies arrived at similar conclusions. A study in Australia showed that a partial replacement of meat and milk with PBAs resulted in a smaller reduction for protein intake, with less than 5% difference in nutritional intakes from baseline diets, when compared with complete replacement [31]. These findings were corroborated in another study where the complete replacement of meat and dairy with PB alternatives in children aged 2–6 y led to lower protein intakes than baseline diets or partial replacement [55]. However, these differences were only significant among boys when complete replacement was compared with baseline. When compared with the EAR, dietary protein, while consumed at lower quantities, still met the requirements for all age-sex categories [55]. Generally, daily protein requirements are based on nitrogen-balance analysis from a known protein content of a diet [95], but whether these requirements would change in a diet consisting only of PSPs has not been adequately determined. Recent evidence from nitrogen-balance studies on males following strict vegan diets for at least 1 y suggests that the established RDA of 0.8 g/kg/d is likely inadequate [95]. This could be due to poorer amino acid composition and digestibility in PSPs. Overall, results from these studies imply that small quantities of alternatives may not lead to significantly different nutritional outcomes when compared with baseline diets. Future research is required to determine the level of replacement and its association with nutritional and/or health outcomes. Based on the replacement models of graded increase from 25% to 100% in the UK population, significant reductions in protein intake ($P < 0.05$) were already observed at the 25% replacement [63]. These studies have shown that higher quantities of replacement may incur more negative implications, not only for protein intake but also for other nutrients, depending on the ingredient composition, quantity of fortification, and the prevalence of consuming these foods. Therefore, complete replacement may be unrealistic in its departure from the typical diet of whole foods or when the cost of these foods is considered.

The lack of clinical evidence on the impacts and long-term health consequences of PBAs [90,94] means that analysis of their nutritional composition is required before they can be recommended as a staple part of meals or complete replacement of ASFs. When compared with a vegan diet that is high in whole fruits and vegetables, one that includes the consistent intake of processed PB products, which are high in sodium and SFA, may cause adverse outcomes. This is particularly true for older adults who are more susceptible to risk factors for hypertension [96]. More research is also needed to consider the AA composition and digestibility of PBAs, which would then establish sufficiency of PBAs as a dietary source for protein. These were areas not analyzed by the dietary scenarios of the studies in this review and require experimental identification. Outside of the consideration of factors such as animal welfare, the necessity of following a vegan diet is challenged, especially if diets optimized with animal foods can achieve positive nutritional, health, and equal environmental outcomes [97].

Simulating PB Diets for Special Populations

The dietary transition to PB diets must involve the consideration of individual variability and examine the impact on individuals who have different nutritional needs [31,98]. The current protein intake recommendation of 0.8 g/kg/body weight [99] is based on nitrogen-balance studies in healthy young males to avoid loss of lean body mass [66] and prevent deficiency [100]. Protein intake based on this requirement needs to be high quality, with DIAAS of 1.0 or more, and a balance of all AAs [14]. Moreover, 0.8 g/kg/body weight is likely inadequate for populations with higher protein demands, such as pregnant and lactating females [14,101], infants and young children [101], and older adults [67,101]. Higher quantities are thus more difficult to attain in a PB diet.

Furthermore, the limiting IAA of protein sources can vary depending on the age of the consumer, owing to differing IAA requirements [98]. Although most limiting IAAs for children, adolescents, and adults are lysine, methionine + cysteine (sulfur AAs), phenylalanine, and tyrosine are more commonly limiting among infants [98]. By contrast, leucine, the branched-chain AA that is important for muscle protein synthesis, may be more limiting for older adults [66,102] who experience increased loss of skeletal muscle mass and higher resistance to postprandial muscle protein metabolism [76,103–105]. The risks of protein and AA deficiency in older adults become more pronounced in PB diets because plant proteins may not induce the same intensity of muscle protein synthesis as ASPs [105].

Examples of protein inadequacy were simulated from the replacement of animal foods with habitually consumed plant foods among United States children, adolescents, and older adults [64–66] (Table 5). In particular, the proportion of children not meeting the EAR for protein tripled when compared with that at baseline (1.9% ± 0.3% to 5.6% ± 0.6%) in scenarios of complete replacement [64]. A reduction of 10 g/d of protein intake was observed among adolescent girls (63.7 ± 0.9 g to 54.0 ± 1.0 g) in scenarios of complete replacement [64]. These observations were attributed to inadequate consumption of high-protein plant foods, such as LNS and soy, and a higher consumption of grain-based food [66], which have higher energy to protein ratios than those in LNS [60]. These corresponding findings illustrate that if a shift toward a PB diet occurs, the risks of protein deficiency become elevated for these populations if more grain-based foods instead of LNS were chosen.

As addressed in the Indonesian study [39], the nutritional needs of some individuals may not be met in diets lower in animal proteins, which provide valuable nutrients beyond protein, needed in elevated growth stages of life. To meet specific protein and micronutrient (iron) requirements for adolescent and lactating females, the complete elimination of meat was unachievable in optimized diets because more diverse protein sources (including ASFs such as red meat and poultry), totaling up to 150 g of protein per day, were required [39]. A similar outcome was observed in another diet optimized for nutrition where relative contribution of animal protein had to be higher for females than that for males, to meet higher iron requirements [10].

Although vegan diets are still relatively infrequent among the current population of older adults, this may increase over the next few decades [106] owing to its present popularity among adults in Western populations. A higher protein intake per day of 1.0–1.2 g/kg/d is recommended by the European Geriatric Medicine Society and several scientific associations for the maintenance of muscle mass and function [103].

The United States studies modeled dietary scenarios of increasing PB foods and dairy products on nutrient intake among older adults (51–70 y, and 71 y and older) [66], adults and children [64], and adolescent girls of 9 to 18 y [65] and compared these results with the those of baseline diets. Doubling dairy consumption to meet required servings for each age group per day showed marked improvement in protein intake and reductions in the proportion of the population that was consuming below the EAR [64–66]. For example, among older adults, the dairy model increased protein intake by 12% and the proportion falling below EAR decreased to 1% [66]. However, the concomitant decrease in energy intake from nutrient-poor foods to displace higher caloric intake from dairy was not modeled, resulting in a lack of information about energy balance [66].

Milk is an important provider of not only protein and IAA but also other essential nutrients [84,107]. ASPs such as lean meat and milk are protein-dense whole foods that supply a higher proportion of absorbable AAs than PSPs, to efficiently fulfill the physiologic requirements of humans [68,108,109]. Indeed, the authors of this United States study highlighted the importance of dairy products to supply critical nutrients. For example, 18% of protein could be provided by 2 daily servings of dairy products (milk, cheese, and yogurt), alongside small proportions of caloric intake (10%), total fat (14%), SFA (26%), and sodium (11%) [64]. Dairy is thus valuable as a food group to efficiently contribute vital nutrients, particularly for certain populations (older adults and young children) who may experience difficulties with the lower digestibility of plant proteins [110]. These benefits will be absent in a vegan diet.

The decrease in protein intake from milk was more pronounced among Australian young children (2–3 y) under scenarios of replacement, with an estimated 7.4% decrease in dietary protein if all dairy milk was replaced with PB beverages comprising 47.6% soy, 44.2% almond, and 8.2% other, with no changes to original intake of meat [31]. Alongside this decrease was the reduction of other vital nutrients (eg, vitamin B12, calcium, and iodine), establishing the importance of ASPs for micronutrient delivery particularly for populations with higher requirements [111]. These results may carry adverse nutritional implications, particularly for children not consuming dairy. In 2 other PB scenarios on young children in the Dutch population, it was observed that although partial and complete replacement of meat to plant alternatives led to no differences in age-specific and sex-specific EAR, the authors had assumed sufficient intake of protein would lead to adequate provision and balance of essential AAs [55]. However, this conclusion may be erroneous without a protein quality analysis. In corroboration, several studies have found evidence of poor protein content in PBBs, which varied greatly depending on the ingredient [112] and consumer behavior (shaken or unshaken) [48]. Almond and oat milk were found to have less than half the protein of soy, goat, and cow milk [113]. In an analysis of 148 PBBs, only 26% of PBBs had at least 5 g of protein per serving, and these were from beverages formulated with soy and pea protein [112].

Discussion

This review provides a summary of dietary models simulating PB diets and outlined the main nutritional outcomes for protein as a consequence of animal to plant protein substitution. Protein intake from PB diets were sufficiently examined in all studies, but analysis of protein quality was only evident in 4 studies. Based on the studies reviewed, protein intake generally decreases with increasing quantities of replacement, but this does not always lead to intake falling below daily reference targets for protein. However, risks of nutrient deficiencies (especially micronutrients) are a concern, as is sufficient protein absorption for special populations who require higher protein intakes to cater for specific physiological needs. Protein adequacy for these individuals may be compromised by a high intake of plant foods that provide reduced digestible IAAs at a higher caloric density [69]. By contrast, dietary scenarios incorporating novel PBAs demonstrate inconsistencies regarding protein intake and quality, owing to variability in their formulated ingredients. Importantly, the addition of PBAs into the diet needs to consider balanced micronutrient profiles on top of protein adequacy if healthy PB diets are to be achieved. Although soy appears to be the best plant protein for inclusion, a combination of plant foods is optimal to accommodate the limiting amino acids of different plant sources. This is an underexplored area in the dietary simulation literature. Furthermore, the choice of a balanced PB diet is highly dependent on the consumer. For example, a PB diet high in LNS will provide very different and more suitable AA profile compared with one that is high in refined grains.

Several limitations were uncovered regarding analyzing the nutritional outcomes of PB dietary scenarios. First, a fair comparison is challenged owing to heterogeneous study methods, leading to ineffective pooling of results. Second, many studies have based nutrient intake data on dietary recalls of a reference population, which may be compromised by inaccuracies in reporting and diversion from usual dietary intakes. Third, most reference diets used in the dietary scenarios are the habitual diets of the population surveyed, further challenging the pooling of results across countries due to inherent differences in cultural diets. Only 1 study in this review has examined nutritional outcomes from a developing country [39]. Representation of populations in these regions are largely absent, but they face higher risks of nutrient deficiency than those in higher-income countries if meat [114] and other ASFs are restricted.

Modeling studies are often limited by insufficient information about health impacts, measurements of confounding factors, and unclear reporting of sensitivity analyses [37]. The evaluation of dietary models depends on the choice of foods selected, which differ culturally and vary in the level of processing. For example, protein isolates would provide higher protein content and availability of IAAs than raw plant materials [26,40,115,116]. These variables eventually affect assumptions of nutritional outcomes.

This review has not considered the consumption of other processed foods such as chips, condiments, and sugar-sweetened beverages. Fortification in PBAs and supplementations have also not been included in the analysis. The nutrition profile of PB diets is expected to alter when these are added in dietary models, especially for micronutrient intake [10] but relatively few studies have examined this.

To further understand the complexities involved in PBA additions to PB diets, future investigations on substitutions of animal-based to PB dietary scenarios should consider if varied quantities and frequency of consumption may lead to different nutritional outcomes. The few studies in this review with such considerations show that inclusion of small quantities may not incur the same negative nutritional outcomes compared with complete replacement [31,55,63]. Furthermore, with an increasing number of PBA consumers and high market demand for these foods, it is crucial to consider their nutritional impacts across all age groups, particularly for special populations who may not receive sufficient quality intake from a diet high in these alternatives.

Author contributions

BXPS, NS, PvH, and WM were responsible for the research design, critical analysis, and review of the manuscript**; PS: analyzed the results and wrote the paper**; and all authors: read and approved the final manuscript.

Conflict of interest

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