Science Letters ISSN 2345-5463 DOI: https://doi.org/10.47262/SL/14.2.132026310

Review article
2026 | Volume 14 | Issue 2 | Article ID 1326310sl

ARTICLE INFO

Received
July 13, 2026
Revised
September 1, 2026
Accepted
September 3, 2026
Published
November 06, 2026

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Keywords
Plant-based meat alternatives
Ultra-processed foods
Nutritional quality
Public health
Consumer perception
Plant-based diets

How to Cite
Imtiaz I, Sami R, Qureshi SK, Yousaf AA, Mujahid N, Samee A, Javed MA. Ultra-processed plant-based meat alternatives: nutritional quality, health implications, consumer drivers, and public health perspectives. Science Letters 2026; 14(2):1326230sl

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Ultra-Processed Plant-Based Meat Alternatives: Nutritional Quality, Health Implications, Consumer Drivers, and Public Health Perspectives

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Abstract

Plant-based meat alternatives (PBMAs) have progressed from niche products to mainstream foods, driven by health, animal welfare, and environmental concerns. Many PBMAs are formulated from protein isolates, refined oils, and additives, so the NOVA system classifies them as ultra-processed. These products are often promoted as healthier alternatives to meat. This article critically evaluates evidence on PBMAs' classification, production technologies, food safety considerations, nutritional composition, health implications, consumer determinants, and sustainability and public health relevance. In general, PBMAs contain less saturated fat and no animal-source cholesterol than red and processed meats. PBMAs also contain more dietary fiber, and replacing meat with PBMAs in a diet reduces LDL cholesterol. However, many products exceed recommended sodium levels, often have lower protein content than meat, and frequently have incomplete amino acid profiles, with methionine and lysine most commonly limiting. Vitamin B12 depends on fortification, which varies and is not standardized across products, and PBMA-specific data on iron and zinc bioavailability are limited. Evidence on gut and metabolic outcomes comes from a few short-term human studies, modeling studies, and inconclusive animal experiments, which must be interpreted separately; long-term human evidence is lacking. Consumer acceptance depends on taste and price, as well as perceived naturalness and a health halo. Environmental impacts are lower than meat but higher than minimally processed legumes. Overall, the evidence somewhat supports using well-developed PBMAs as transitional foods to reduce red and processed meat consumption, but not as alternatives to minimally processed whole plant foods. Priorities include long-term, independently funded trials; nutrient standardization; better labeling; food safety assessment; and research in low- and middle-income countries.

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Introduction

Dietary patterns worldwide have shifted toward plant-based diets, driven by concerns about the environment, health, and animal welfare [1]. Nevertheless, global meat consumption continues to rise and is projected to keep growing [2], increasing interest in products that reduce reliance on animal meat while preserving familiar eating experiences. As part of this trend, plant-based meat alternatives (PBMAs) have moved from a niche market to common products sold in supermarkets and fast-food and restaurant chains, and are enjoyed by flexitarians as well as vegetarians. Innovations in plant protein technology have helped drive this expansion by making plant proteins more similar in texture, flavor, and appearance to meat [3].

Although PBMAs are popular, their nutritional benefits are somewhat questionable. Often advertised as healthier than meat, they also use many industrial chemical processes and ingredients and, as such, many are classified as "ultra-processed foods (UPFs)" in the NOVA classification of foods [4]. This raises a key question about their suitability for a healthy, sustainable diet [5]. However, this classification depends on formulation and is not universal. An umbrella review of meta-analyses of observational studies has associated higher exposure to UPFs with a greater risk of adverse health outcomes, particularly cardiometabolic outcomes and mortality [6]. This creates a paradox: a product perceived as healthy may be high in sodium, additives, and refined ingredients [7]. Two considerations complicate the paradox. First, people consume PBMAs as substitutes for meat rather than in addition to it, so the relevant comparison is often with red and processed meat, which are themselves frequently ultra-processed. Second, UPF research has rarely analyzed PBMAs as a separate category, and direct evidence on their long-term health effects is scarce [8]. Recent audits illustrate the tension: in a UK audit, all PBMAs and most conventional meat products were classified as ultra-processed, yet PBMAs scored better on a nutrient profiling model than standard meat products [9].

Existing reviews have examined PBMAs from complementary angles, including production technology, nutritional composition and health effects, consumer determinants [8] and, in an interdisciplinary synthesis, technological, nutritional, environmental, market and social challenges [1]. The present review advances beyond these syntheses in five ways. First, it focuses explicitly on the ultra-processing paradox, examining how NOVA classification varies with formulation and how nutrient profile and degree of processing can point in different directions for the same product. Second, it links production technologies to nutritional composition, texture, and food safety rather than treating them separately. Third, it distinguishes evidence strength by study type, separating human intervention trials from modeling studies and animal experiments. Fourth, it places PBMAs within a hierarchy between animal meat and minimally processed whole plant foods and evaluates whether they are best viewed as transitional foods. Fifth, it considers public health implications, including affordability and access in low- and middle-income countries (LMICs), where most evidence gaps lie. It includes recent human, modeling, and animal studies published up to 2026. This review therefore critically examines the classification, production, nutritional composition, and health implications of PBMAs, as well as consumer motivation factors and how these might be leveraged in public health strategies. Throughout, PBMAs refer to formulated meat analogs; traditional plant protein foods such as tofu, tempeh, and seitan, and whole legumes are considered only as reference points.

Review methodology

We conducted a narrative literature review using Scopus, Web of Science, and Google Scholar. The search covered publications from January 2019 to July 2026; we included earlier foundational sources (for example, the NOVA classification and the evaluation of processed meat carcinogenicity) where needed to define concepts. Searches combined terms for the product category ("plant-based meat alternatives", "meat analogs", "meat substitutes") with terms for each theme of the review ("ultra-processed foods", "NOVA", "extrusion", "nutritional composition", "protein quality", "fortification", "health effects", "gut microbiota", "food safety", "consumer perception", "environmental sustainability" and "affordability") using Boolean operators, and the reference lists of key articles were screened manually.

Study selection followed two stages: we screened titles and abstracts for relevance, then assessed full texts of potentially eligible articles. Peer-reviewed articles published in English were eligible if they examined PBMAs (formulated meat analogs) and addressed at least one of the themes of the review: classification, processing, nutritional composition, health outcomes (human intervention, observational,

modeling or animal studies), consumer behavior, sustainability, food safety or public health policy. Studies were excluded if they focused solely on traditional plant protein foods (tofu, tempeh, seitan) or whole legumes without comparison to PBMAs, if they were not peer-reviewed (for example, conference abstracts or opinion pieces), or if they lacked sufficient scientific detail. We prioritized recent studies because PBMA formulations and the market are changing rapidly, so older nutritional audits and consumer surveys may not reflect currently available products. Where available, we preferred studies directly comparing PBMAs with animal-based meat, and we used product audits, modeling studies, and review articles mainly to provide context. We extracted findings by theme and synthesized them narratively, classifying evidence by study design (human intervention, observational, modeling, animal, product audit, or *in vitro*) to interpret its strength appropriately.

Definition and classification of ultra-processed PBMAs

Definition of PBMAs

PBMAs are formulated products derived from plant ingredients such as soy, pea, and wheat protein, processed to emulate meat's functional and sensory attributes, including flavor, texture, and appearance [3]. They differ from traditional plant-protein foods (tofu, tempeh, and seitan), which have long been used as meat substitutes, especially in Asia [2], or as whole-legume products. This is because the terms are not used uniformly: in the literature, "plant-based meat", "meat analog", "meat substitute", and "meat alternative" are used interchangeably, making it hard to compare studies. For clarity, this review uses the term PBMAs to denote formulated meat analogs only (for example, burgers, sausages, nuggets, and minced products). Traditional plant protein foods and whole legumes differ in ingredients, processing, and nutritional composition; therefore, we treat them as separate reference categories (Section 10.2), do not pool them with PBMAs, and do not extrapolate findings to PBMAs.

NOVA classification and ultra-processing

In the NOVA system, ultra-processed foods are industrially processed foods that consist primarily of substances extracted from foods or produced in laboratories and, in very few cases, whole foods kept in their natural form. Typical ingredients in PBMAs include protein isolates, refined oils, flavorings, binders and stabilizers, and colorants. In a German market analysis, 88% of plant-based meat products were identified as ultra-processed products, compared with 52% of their meat-based counterparts

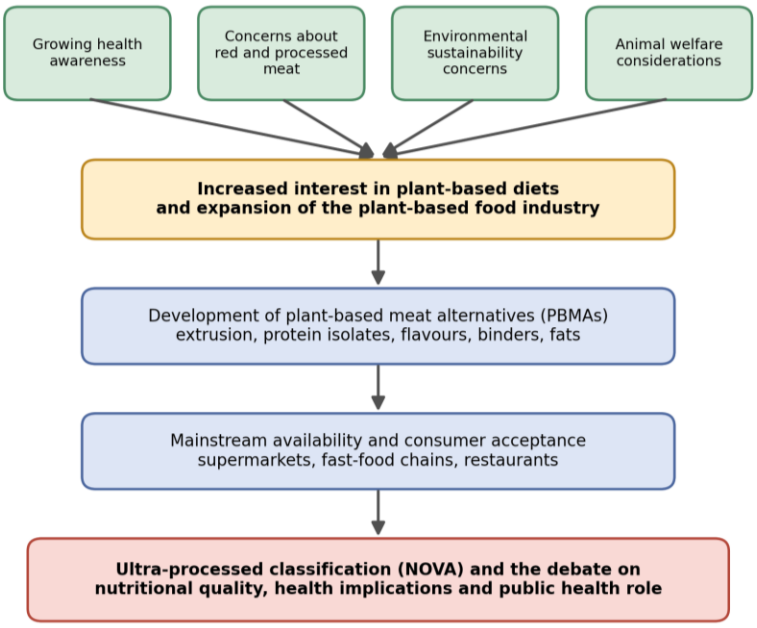


Fig. 1 Social, environmental, and health-related drivers of plant-based diet trends and the emergence of ultra-processed plant-based meat alternatives.

(282 plant-based and 149 meat-based products) [10]. Importantly, ultra-processed status is not universal within the category. NOVA classification is applied at the level of the individual product and depends on the ingredients and processes used: products containing industrial ingredients and cosmetic additives such as protein isolates, modified starches, emulsifiers, flavorings and colorants are classified as ultra-processed, whereas products made mainly from minimally processed ingredients with limited additives (for example, simple legume- or vegetable-based patties) may fall into a lower NOVA group. The proportion of products classified as ultra-processed therefore differs between markets and audits [9, 10], and statements in this review about ultra-processing refer to the products examined in the cited audits rather than to every PBMA. The health relevance of this classification is contested. Observational evidence links UPF intake with obesity, cardiometabolic disease and mortality [6], although the mechanisms remain uncertain [11]. Because NOVA classifies foods by degree of processing rather than nutrient content, some authors have proposed reassessing how UPF frameworks treat meat alternatives [12]. Fig. 1 summarizes the trends that led to the emergence of PBMAs and to this debate.

Types of PBMAs

The PBMA market includes burgers, sausages, nuggets, and minced products, as well as, more recently, seafood analogs such as plant-based fish fillets and shrimp substitutes [13]. Products differ in formulation and processing intensity: burgers and sausages may rely on textured vegetable protein and flavor systems, whereas reproducing fibrous textures requires more elaborate structuring. This diversity means that nutritional and health conclusions cannot be generalized across the category.

Production technology

Raw materials and ingredients

Most PBMAs are based on soy, pea, or wheat gluten, selected for functional properties such as solubility, water- and oil-binding capacity, gelation, and emulsification. Protein isolates are widely used and typically contain more than 75% protein, but wet fractionation is resource-intensive, and dry fractionation yields less-refined concentrates [2]. Fats such as coconut, sunflower, and canola oil improve juiciness and mouthfeel, while flavorings, colorants, and binders enhance sensory properties and shelf life. For example, a recent rat study examined a commercial pea-protein product that listed rapeseed and coconut oils, flavorings, methylcellulose as a stabilizer, sunflower lecithin as an emulsifier, and beetroot coloring [14]. These ingredients are essential to product quality and also contribute to the ultra-processed character of PBMAs.

Processing techniques

Extrusion is the predominant technology for producing meat analogs because it is productive, cost-effective, adaptable, and scalable. Heat, pressure, and shear transform globular plant proteins into aligned, fibrous structures. Alternative structuring approaches include shear-cell processing, three-dimensional printing, wet spinning, and electrospinning [2, 3]. Processing can affect nutritional quality. *In vitro* digestion showed impaired digestion of a plant protein blend during high-moisture extrusion, which negatively affected postprandial amino acid availability in humans [15]; during heat treatment, some essential amino acids, such as lysine, may be degraded via the Maillard reaction [16]. High-pressure processing (HPP), a non-thermal technology, has been reviewed mainly for animal-derived ultra-processed meat products, where energy demand and scalability are recognized constraints [17]; its application to PBMAs is therefore largely extrapolated from meat research. Table 1 summarizes how the main processing steps affect nutritional composition, texture, and final product characteristics. In low-moisture extrusion, proteins are texturized into dry, porous textured vegetable protein, then rehydrated and combined with binders, fats, and flavorings; the resulting products suit minced, nugget, and burger formats but depend heavily on added ingredients for juiciness and binding. High-moisture extrusion uses a cooling die to produce aligned, fibrous structures closer to whole-muscle meat, but, as noted above, the intense thermal and mechanical treatment may reduce digestibility and lysine availability [15, 16]. Structuring technologies such as shear-cell processing, three-dimensional printing, wet spinning and electrospinning can generate more complex fibrous or marbled architectures, but they are mainly at laboratory or pilot scale and data on their nutritional effects are scarce [2, 3].

Upstream and downstream steps also matter. The protein ingredient (isolate, concentrate, or flour) determines protein content, with wet fractionation yielding purer but more resource-intensive isolates and dry fractionation yielding less refined

Table 1 Effects of main processing steps and technologies on the nutritional composition, texture and product characteristics of plant-based meat alternatives.

Processing step or technology	Effects on nutritional composition	Effects on texture and product characteristics
Protein ingredient fractionation	Wet fractionation yields protein isolates (typically >75% protein) but is resource-intensive; dry fractionation yields less refined concentrates [2]	Functional properties (solubility, gelation, emulsification, water- and oil-binding) influence texture and binding
Low-moisture extrusion (textured vegetable protein)	Nutritional outcome depends largely on added fat, salt and binders; product-dependent	Dry, porous, granular texture suited to mince, nuggets and burgers; juiciness depends on added ingredients
High-moisture extrusion	Impaired *in vitro* digestion and delayed postprandial amino acid availability for one protein blend [15]; possible lysine loss through Maillard reactions [16]	Aligned, fibrous, whole-muscle-like structure; productive and scalable [2, 3]
Shear-cell, 3D printing, wet spinning, electrospinning	Limited data on nutritional effects; mostly experimental or pilot scale [2, 3]	Allow fibrous, marbled or complex structures; scalability and cost remain constraints
Addition of fat, salt, binders and flavorings	Determines saturated fat (for example, coconut oil), sodium and additive load [2, 14, 25]	Provides juiciness, mouthfeel, binding, color and flavor masking; contributes to ultra-processed character
High-pressure processing and preservation	Evidence reviewed mainly for animal-derived meat products; application to PBMAs largely extrapolated [17]	Shelf-life extension; energy demand and scalability are constraints [17]

concentrates [2]. Downstream, the type and amount of fat, salt, binders, and flavorings added to achieve juiciness, binding, and taste determine saturated fat, sodium, and additive load, so two products with similar texture can differ substantially in nutritional composition. Because the same structuring technology can yield products with very different formulations, nutritional quality cannot be inferred from the processing method alone, so PBMAs should be evaluated product by product.

Additives and food engineering

To replicate the sensory experience of meat, PBMAs rely on flavorings, emulsifiers, binders, and colorants. Colorants such as leghemoglobin and beet extracts reproduce the appearance of raw and cooked meat, and flavorings mask undesirable tastes of some legume proteins. Careful formulation lets manufacturers closely approximate conventional meat, but the long-term health effects of additives such as emulsifiers remain poorly characterized, and this uncertainty contributes to the ultra-processing controversy [14].

Food safety considerations

Food safety is an important but comparatively under-studied dimension of PBMAs. Most of the PBMA literature reviewed here addresses nutrition and health rather than safety, so this section outlines the principal hazards that follow from ingredients, processing and storage, drawing on general knowledge of plant protein and processed food systems. It should be read as an indicative overview rather than a systematic hazard assessment. Ingredient-related concerns include allergens: soy and wheat (gluten) are major food allergens, and ingredients such as pea, lupin, or nuts can also trigger reactions; shared production lines can also cause unintended cross-contact, making clear allergen labeling essential. Plant raw materials may also carry contaminants such as mycotoxins, pesticide residues, and heavy metals (for example, cadmium in some legumes and oilseeds) that can carry over into protein isolates and concentrates, so supplier specifications and ingredient testing are important. Heat treatment largely reduces naturally occurring antinutritional factors, including trypsin inhibitors and phytates, but they may persist if processing is inadequate. Novel ingredients, such as heme proteins produced by recombinant fermentation, require regulatory safety assessment, and the long-term effects of additives, including emulsifiers and stabilizers, are not well characterized [14]. Processing-related concerns include heat-induced reaction products. High-temperature extrusion and cooking can generate Maillard reaction products and, depending on formulation, compounds such as acrylamide; lipid oxidation can also occur in products rich in unsaturated oils. The relevance of these to PBMAs requires further study [14, 16].

Microbiological safety and storage also deserve attention. PBMAs are typically moist and protein-rich and are often sold as minced or ready-to-cook chilled products, conditions that can support spoilage organisms and pathogens if hygiene or temperature

control fails; raw plant ingredients can carry spore-forming bacteria and enteric pathogens. Cross-contamination during handling, post-processing contamination, and cold-chain failures are practical risks, particularly where refrigeration infrastructure is limited. Shelf life depends on the preservation strategy (chilled, frozen, or thermally processed), packaging, and water activity, and manufacturers may rely on preservatives, acidulants, or high-pressure processing, whose application to PBMAs is largely extrapolated from meat research [17]. Overall, PBMA-specific safety surveys and shelf-life studies remain scarce. Consumers should follow storage and cooking instructions as with other perishable protein foods, and manufacturers and regulators need clear allergen labeling, ingredient specifications, and validated shelf life.

Nutritional quality and composition

Protein quantity and quality

Protein content varies widely among PBMAs. In a Dutch analysis, total protein content was lower in most meat analogs (80%) than in animal-based counterparts [16], and a five-country European comparison found that red meat products had significantly higher protein, fat, saturated fat, and salt contents than meatless alternatives, which contained more carbohydrate and fiber [18]. However, in a small Turkish sample, meat analogs' protein content (18.5%) was similar to that of meat products (18.1%) [19], highlighting the category's heterogeneity. Protein quality often matters more than quantity. In an analysis of 40 commercially available analogs [16], the sum of essential amino acids was adequate in nearly all products, but every analog was deficient in at least one specific essential amino acid; methionine was low in 39 of 40 products and lysine in 11 of 40, and amino acid profiles varied irrespective of the protein source used. Limiting amino acids in such analyses are generally identified by comparing essential amino acid content per gram of protein with a reference requirement pattern (for example, the FAO/WHO scoring pattern), the lowest ratio defining the first limiting amino acid; the reference pattern, the protein basis, and whether digestibility is taken into account (for example, through PDCAAS or DIAAS) differ between studies and influence which amino acids are flagged. These findings describe the products sampled and should not be generalized to all PBMAs, whose amino acid profiles depend on protein source, blending, and processing. Digestibility is also product-dependent: in an *in vitro* study, protein digestibility was lower in plant-based steaks but higher in plant-based cured meats than in their meat counterparts, and overall quality depended on the blending of protein sources and on processing [20]. A systematic review of 19 human intervention studies reported lower protein bioavailability and a smaller rise in plasma essential amino acids after PBMAs than after animal meat, although muscle protein synthesis and physical performance were not affected [21]. Suggested strategies include fortifying PBMAs with limiting free amino acids, blending proteins, and combining PBMAs with complementary foods such as cereals within a meal.

Fat composition

PBMAs generally contain less energy, total fat, and saturated fat than comparable animal-derived products, as shown in a Canadian food-supply analysis [22] and a European comparison [18], and, as plant products, they contain no animal-derived cholesterol. However, the benefit depends on the formulation: using coconut oil, which is rich in saturated fat, as a fat source [2] shows why product-by-product saturated fat content still needs to be checked.

Micronutrients and fortification

Plant ingredients do not provide vitamin B12, so manufacturers must fortify them, and fortified PBMAs often seek to match meat's nutritional profile [23]. However, fortification practices vary and are not standardized: whether a product is fortified, which nutrients are added, in what chemical form, and at what level differ between manufacturers, product types, and countries, and in a UK audit, few PBMAs reported micronutrient information [9]. Fortification is largely voluntary in many markets and is not tied to a common reference such as the nutrient content of the meat being replaced, so commercial PBMAs lack standardized nutrient profiles, and consumers cannot assume that a given product provides vitamin B12, iron, zinc, or other nutrients in amounts comparable with meat. Dietary modeling in French adults suggested that replacing meat and dairy with plant-based substitutes could increase the risk of riboflavin and vitamin B12 deficiency, and that substitutes containing legumes were nutritionally more adequate than others [24].

Evidence on iron and zinc should be interpreted at two levels. In plant foods generally, antinutrients such as phytates inhibit mineral absorption, so iron and zinc from plant matrices are less bioavailable

than from meat. For PBMAs specifically, however, direct bioavailability data are scarce: absorption is likely to depend on the protein ingredient, the phytate content of isolates and concentrates, the form of any added iron or zinc, and enhancers or inhibitors in the meal, which have been little studied in PBMA products [23]. Mineral bioavailability from PBMAs is therefore uncertain, not established, and inferences from general plant-food evidence should not be read as PBMA-specific findings. Without careful dietary planning, substituting meat with PBMAs may risk micronutrient inadequacy, particularly where products are unfortified. Harmonized fortification targets, standardized nutrient declarations and independent verification of nutrient content would help address this variability.

Sodium and additive content

Sodium is one of the most consistent nutritional concerns. In a UK survey of 207 plant-based and 226 meat products, nearly three-quarters of the plant-based products did not meet national salt targets, although they had a better overall nutrient profile than their meat equivalents on the UK nutrient profiling model [25]. Relative to animal products, sodium findings differ between studies: Canadian meat analogs had lower sodium than animal-derived products [22], whereas modeling suggested that meat-substitute use could raise sodium intake and partly offset benefits. Highly processed formulations add salt for flavor, preservation, and texture, and PBMAs also contain additives whose long-term effects are uncertain [7, 14].

Comparison with animal meat

Table 2 summarizes the nutritional comparison between PBMAs and animal meat. PBMAs offer advantages in lipid composition and fiber, but many products have lower protein quantity and quality, variable micronutrient profiles, and often high sodium. Their nutritional value therefore depends strongly on the product and formulation [26]. Comparisons of PBMAs with meat in Table 2 and Table 7 should be interpreted with caution. Nutrient values come from studies that differ in product selection and formulation, serving or portion size (per 100 g versus per serving), cooked versus raw state, and analytical approach (label data versus laboratory analysis, and different methods or conversion factors for protein and energy), and the products sampled reflect specific markets and time points. The tables are therefore intended as qualitative summaries of direction rather than precise quantitative comparisons.

Health implications of ultra-processed PBMAs

Evidence on the health effects of PBMAs comes from different study types that vary markedly in strength and relevance, and this section distinguishes them throughout. Human intervention studies provide the most direct evidence but are short and involve few products; modeling and simulation studies estimate

Table 2 Nutritional comparison between plant-based meat alternatives and animal meat.

Nutritional aspect	PBMAs	Animal meat
Protein quantity	Lower in most analogs, with wide variation between products [16, 18]	Higher per 100 g in red meat products
Protein quality	Essential amino acid profile incomplete in many of the products analyzed (methionine and lysine most often limiting); varies with protein source and blending; digestibility product-dependent [16, 20]	Complete, highly digestible protein
Fat profile	Lower total and saturated fat on average; no animal-derived cholesterol; formulation-dependent [22]	Higher saturated fat in red meat; contains cholesterol
Fiber	Present in many products [18]	Absent
Micronutrients	Variable and not standardized; vitamin B12 and other nutrients depend on fortification; PBMA-specific iron and zinc bioavailability data limited [23]	Naturally rich in vitamin B12, iron and zinc
Sodium	Frequently above recommended targets [25]; ranges widely	Variable; high in processed forms
Processing level	Frequently ultra-processed; varies with formulation [9, 10]	Ranges from unprocessed to ultra-processed

Note: Values and statements are indicative. Differences in product formulation, serving size, cooking state, and analytical methods between source studies limit direct quantitative comparison.

Table 3 Summary of potential health implications of plant-based meat alternatives consumption.

Health domain	Potential benefits	Potential risks or uncertainties
Cardiovascular	Human evidence: lower LDL cholesterol in a short-term randomized trial; lower saturated fat [27]	High sodium; human trials short and partly industry-funded; modeling studies depend on assumptions
Metabolic	Human evidence: modestly lower body weight and increased satiety in short-term studies [21]	Observational UPF evidence, not PBMA-specific [6]; animal evidence: greater visceral fat in a rat study [14]
Inflammation and oxidative stress	Human evidence: no differences in several metabolic markers in one trial [27]	Conflicting results; limited long-term human data [21]
Gut health	Human evidence: small favorable microbial changes in a 4-week real-world study [31]	Animal evidence: dysbiosis and intestinal oxidative stress in some rat studies [32]
Cancer risk	Inferred, not PBMA-specific: potential reduction in exposure to processed-meat-related compounds when substituting [44]	No direct evidence on PBMAs and cancer
Nutrient adequacy	Fortified products can supply vitamin B12	Modeled risk of B12 and riboflavin deficiency; lower protein quality [28]

Note: Evidence types are indicated because human intervention, observational, modeling, and animal studies differ in strength and are not directly comparable; animal findings cannot be extrapolated directly to humans.

population-level effects of hypothetical substitutions, and depend on their assumptions rather than on observed outcomes; observational studies concern ultra-processed foods in general and rarely isolate PBMAs; and animal experiments offer mechanistic insight but cannot be extrapolated directly to humans because of differences in physiology, diet composition, and dose. Findings are labeled by study design to avoid conflating these levels of evidence.

Cardiovascular health

Lower saturated fat and the absence of cholesterol may favor lipid profiles, whereas high sodium is a recognized risk factor for hypertension. Controlled intervention evidence is limited but supportive. In the eight-week SWAP-MEAT randomized crossover trial in generally healthy adults, LDL cholesterol and body weight were modestly lower during the plant-based meat phase, and trimethylamine-N-oxide (TMAO) was lower in one sequence; a PBMA manufacturer funded the trial through an unrestricted gift [27]. Modeling studies point in the same direction but show heterogeneity: a French microsimulation estimated that replacing meat and dairy with plant-based substitutes could avert roughly 3,700 to 6,700 chronic disease-related deaths per year depending on substitute quality, with higher sodium intake slightly offsetting benefits [28], while earlier simulations found small and heterogeneous effects on diet quality [24] and potentially larger effects if substitutes were optimized for nutritional composition [29]. Thus, PBMAs may offer cardiovascular benefit when low in sodium and saturated fat, but poorly formulated products may offer little.

Metabolic health

Concern about metabolic health arises from the UPF classification [6, 11]. However, PBMAs replace rather than add to other foods, and short-term human trial data did not indicate adverse effects on weight; in SWAP-MEAT, body weight was modestly lower with PBMAs, and several intervention studies report increased satiety [21]. Animal studies are less reassuring, but they are hypothesis-generating only: rats fed a commercial PBMA for three weeks had greater mesenteric and retroperitoneal fat deposition despite lower food intake, but also lower LDL cholesterol and liver weight than pork-fed rats [14], and mice fed PBMAs for 68 days showed greater lipid accumulation than those fed real meat [30]. Extrapolation from rodents to humans is limited, and long-term human data are lacking.

Inflammation and biomarkers

In SWAP-MEAT, no significant differences were reported between diets for fasting glucose, insulin, HDL cholesterol, triglycerides or blood pressure. A systematic review concluded that findings on oxidative stress, inflammation, vascular function, and microbiota composition after PBMA substitution conflict [21]. Trials are short and use a limited range of products, which limits generalizability to the wider, more diverse PBMA market.

Gut microbiota and gastrointestinal effects

Evidence on gut health is limited and mixed, drawing on one small human study and animal experiments, which are discussed separately below. In humans, a four-week real-world study of 40 healthy adults that

replaced at least four meat-containing meals per week with PBMAs was associated with small but statistically significant changes in butyrate-producing bacteria; a manufacturer supplied the products, and the authors concluded the findings were favorable [31]. Animal studies, which cannot be extrapolated directly to humans, report less favorable or mixed outcomes: rats fed commercial PBMAs showed oxidative stress in the intestine and gut dysbiosis [32], and a longer feeding study reported increases in a potentially harmful bacterial genus and metabolic disturbances [33]. Another rat study found both beneficial and less desirable responses to a PBMA diet: higher colonic abundance of bacteria associated with cholesterol metabolism and lower LDL, but higher fecal markers of protein fermentation and increased lipid oxidation in the colonic mucosa [14]. Because outcomes differ by product, species, and design, researchers cannot draw firm conclusions about PBMAs and gut health without long-term human studies.

Cancer and chronic disease risk

Processed meat is known to be carcinogenic to humans, while consumption of PBMAs has the potential to lessen exposure to the carcinogenic compounds from meat [34], if it were to replace it. This reasoning is inferential and based on evidence for processed meat rather than on studies of PBMA consumers. To date, researchers have not directly studied PBMA consumption and cancer risk, and the effects of PBMA additives, processing-related compounds, and changes in gut microbiota remain unknown [8]. This is an important study gap that only longitudinal studies can fill (Table 3).

Consumer drivers, perceptions and market trends

Consumer motivations

Adoption of PBMAs reflects a combination of health, environmental and ethical motives [1]. These factors can drive market growth, but a narrative review concluded they are not sufficient on their own [35]. Health motivation is frequently cited, although perceived healthiness does not always match objective nutritional quality [8].

Barriers to adoption

Sensory quality and price are the most consistent barriers. In a representative survey experiment in the United States, meat had higher average utility than all PBMAs, and PBMA consideration and choice increased noticeably when PBMA prices were reduced, which led the authors to emphasize affordability beyond price parity [36]. A cross-sectional questionnaire of 325 respondents found that perceptions of PBMA products, as well as the importance of food choice motives and barriers, differed across adopter groups, and that manufacturers need to address sensory and health quality, degree of processing, and affordability [37]. Skepticism about processing and naturalness is part of this picture, and a market review likewise identifies consumer acceptance, which depends on appearance and taste, as a major challenge for producers [2].

Marketing and the health halo

Plant-based labeling can create a health halo, leading consumers to assume products are healthy regardless of processing level or composition. PBMA marketing uses nutrition-related claims [38], which may widen the gap between perceived and actual nutritional value. Ethical and symbolic messages may therefore influence purchasing as much as objective nutrition information.

Socio-demographic patterns

In a survey of 1,177 adults in Scotland and England, 47.4% purchased plant-based alternative foods, most often burgers, sausages and mince, whereas greater deprivation was associated with lower purchasing of

Table 4 Determinants of plant-based meat alternatives consumption.

Domain	Key determinants	Implications
Motivations	Health, environmental sustainability, ethics [35]	Contribute to initial adoption but are not sufficient alone
Barriers	Taste and sensory quality, price, concerns about processing [36]	Limit sustained consumption
Perceptions	Health halo associated with plant-based labeling [8]	Possible misalignment with nutritional quality
Demographics	Age, education and urban residence [2]; deprivation [39]	Unequal adoption patterns
Market trends	Innovation, product diversification, price [3]	Growth dependent on sensory quality and affordability

Table 5 Qualitative relative environmental impact of food categories.

Food category	Relative environmental impact	Supporting evidence
Minimally processed whole plant foods (*e.g.*, peas, soybeans, beans)	Lowest	Springmann [42]
Plant-based meat alternatives	Intermediate	Van Vliet et al. [34]
Animal meat (especially red meat)	Highest	Springmann [42]; Van Vliet et al. [34]

whole-food plant proteins and lower knowledge of plant-based protein [39]. Researchers have studied Generation Z consumers in Austria, including their willingness to pay for PBMAs and their perceptions [40], and a market review summarizes prior studies suggesting that younger, more educated, urban consumers are more likely to choose meat substitutes. Research on PBMA acceptance outside Western countries remains scarce [35].

Market growth and industry expansion

The PBMA sector has grown from a niche to a mainstream food category, supported by technological innovation, product diversification, and investment. Future growth is expected to depend on improved sensory quality, lower cost, and better alignment of formulations with consumer expectations [36]. Table 4 summarizes the main determinants.

Sustainability and food system implications

Environmental impact

PBMAs generally have lower environmental impacts than meat, particularly red meat [41], although the magnitude depends on ingredient sourcing, processing intensity, and supply chains. A multicriteria analysis of 24 meat and milk alternatives found that unprocessed plant foods such as peas, soybeans, and beans performed best across nutrition, health, environment, and cost, whereas processed products such as veggie burgers were associated with smaller climate benefits and higher costs than unprocessed foods, yet still offered substantial benefits compared with animal products [42]. Bąkowska et al. [41] similarly conclude that PBMAs can support environmental sustainability, but that further research on safety and quality is needed.

Relative environmental ranking

Table 5 presents a qualitative ranking of food categories based on the cited evidence. PBMAs occupy an intermediate position: better than animal meat, but less favorable than minimally processed whole plant foods.

Role in sustainable diets

PBMAs can serve as a stepping stone away from meat because they mimic its sensory and nutritional properties [9]. Their role should be framed within broader dietary change focused on minimally processed plant foods, and widespread use of PBMAs to replace more nutrient-dense, less-processed plant foods could limit potential health and environmental gains [42]. PBMAs are therefore best conceptualized as enabling tools rather than as ideal end-state dietary components (Fig. 2).

Public health perspectives

Role in dietary guidelines

General nutrition guidelines recommend limiting red and processed meat and “eat more plants”. PBMAs do not fit these guidelines easily because they are often ultra-processed and have variable nutritional value [8]. Data modeling suggests that well-designed substitutes could improve dietary diversity, but the impact will vary with the substitutes' composition [29].

The ultra-processed food debate

PBMAs occupy a paradoxical position: they may displace processed meat while increasing ultra-processed food consumption [6]. Recent work calls for nuanced evaluation that considers nutrient profile and overall dietary pattern in addition to processing level [12].

Policy and regulation

Key policy issues include food classification, nutritional transparency, and labeling. The naming of plant-based products with meat-related terms is a subject of legal analysis [43], and nutrition and health claims in PBMA marketing warrant scrutiny. Audit data suggest that cost-effective fortification and

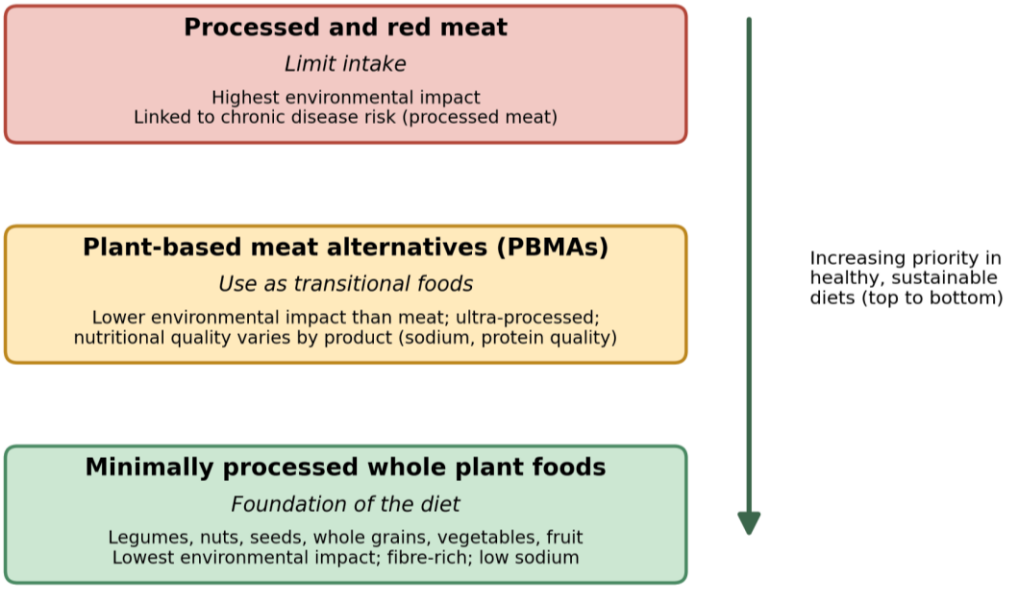


Fig. 2 Proposed role of plant-based meat alternatives as transitional foods within sustainable dietary patterns. The arrow indicates increasing priority in healthy, sustainable diets from top to bottom.

reformulation could improve PBMAs' nutritional quality and affordability. Standardized fortification and nutrient-declaration requirements would also reduce the variability in micronutrient content between products (Section 5.3).

Accessibility and equity

Evidence on price is mixed. In Canada, meat analogs and meat products had no significant price difference [22], whereas in a US experiment, meat was typically cheaper than most PBMAs, and price reductions increased PBMA choice. Social gradients in purchasing and knowledge [39] suggest that PBMAs are not an equitable route to healthier diets, and most data come from high-income settings [35]. Affordability and access are likely to be more pressing in low- and middle-income countries (LMICs), although direct evidence is limited because almost all PBMA research comes from high-income settings. In many LMICs, PBMAs may be imported or sold at premium prices through urban retail and food-service channels, so access is likely to be concentrated among higher-income urban consumers, and cold-chain limitations may restrict the distribution of chilled and frozen products.

Food systems, consumer preferences and nutritional priorities also differ. Meat consumption is lower in many LMICs than in high-income countries, so the main rationale for PBMAs in high-income settings, displacing excess red and processed meat, may be less relevant, while undernutrition and micronutrient deficiencies (including iron, zinc and vitamin B12) remain priorities, making the variable fortification and mineral bioavailability of PBMAs (Section 5.3) directly pertinent. Affordable, culturally familiar plant proteins, including legumes, pulses and traditional fermented or soy foods, may deliver comparable or better nutritional value at lower cost than ultra-processed analogs, and consumer acceptance depends on local cuisine, taste preferences and trust in novel foods, which remain poorly studied outside Western countries [35]. PBMAs in LMICs may therefore be optional, complementary products for specific consumer segments rather than a general strategy for improving diets, and policy should prioritize access to affordable minimally processed plant proteins and fortified foods, along with context-specific research on affordability, consumption, and nutrient adequacy. Table 6 summarizes opportunities and challenges.

Overall public health synthesis

From a public health perspective, PBMAs should sit within a hierarchy in which minimally processed whole plant foods remain the diet's foundation, and well-designed PBMAs can help reduce meat intake. Strategies to improve PBMA quality should focus on nutritional quality (including sodium, protein quality, and fortification), clear labeling, and equitable access, while maintaining emphasis on diets rich in minimally processed plant foods.

Table 6 Public health opportunities and challenges of plant-based meat alternatives.

Dimension	Opportunities	Challenges
Nutrition	Potential to reduce processed meat intake	Ultra-processing, high sodium, variable protein quality and fortification
Sustainability	Lower environmental impact than meat	Less favorable than minimally processed whole plant foods
Policy	Can support dietary transition	Labeling, classification and claims issues
Equity	Expanding food choices for some consumer segments	Cost, social gradients in purchasing, limited access and cold-chain constraints, and limited data from low- and middle-income countries

Table 7 Qualitative comparison of plant-based meat alternatives, animal meat and whole plant foods.

Attribute	Plant-based meat alternatives	Animal meat	Whole plant foods
Protein quality	Variable; incomplete amino acid profile in many analyzed products	High	Variable; improved by combining complementary foods
Fibre	Present in many products	Absent	High
Saturated fat	Variable, generally lower than meat	Higher (red and processed meat)	Low
Sodium	Often above targets	Variable; high in processed forms	Low unless added
Processing	Frequently ultra-processed (formulation-dependent)	Unprocessed to ultra-processed	Minimal
Environmental impact	Intermediate	Highest, especially red meat	Lowest

Note: Qualitative comparison only; differences in product formulation, serving size, and analytical methods between source studies limit direct quantitative comparison.

Comparative analysis

PBMAs versus animal meat

PBMAs typically have lower saturated fat and no animal-derived cholesterol [22], and replacing processed meat could reduce exposure to compounds linked to processed meat [44]. Conversely, animal-source foods provide complete, highly digestible protein and naturally supply vitamin B12, iron, and zinc, whereas many PBMAs depend on fortification and have limited PBMA-specific data on mineral bioavailability [23]. Environmental advantages over meat, especially red meat, are generally substantial, but health benefits remain product-specific, and not all PBMAs are healthier than meat [26].

PBMAs versus whole plant foods

Minimally processed whole plant foods such as legumes, nuts, seeds, and whole grains are rich in fiber and other beneficial components, contain little sodium, and have no industrial additives. By contrast, PBMAs are industrially produced to mimic meat. They can still be useful sources of grains, legumes, plant protein, and fiber, provided that salt and saturated fat content are monitored [45]. Traditional plant protein foods such as tofu, tempeh, and seitan differ from formulated meat analogs in ingredients and processing; we use them here only as reference points and do not pool them with PBMAs in the comparisons above. In multicriteria comparisons, unprocessed plant foods outperform processed alternatives across health, environmental, and cost domains. PBMAs should therefore be regarded as preferable to processed meat in many respects, but not as nutritious or sustainable as diets centered on minimally processed plant foods [46].

Transitional foods versus long-term solutions

PBMAs may facilitate dietary change because their meat-like properties lower the barrier for consumers reluctant to adopt vegetarian diets [9]. Their suitability as long-term staples is less certain because many products are ultra-processed and the long-term health consequences of additives, sodium and extensive processing are poorly understood [7]. It is therefore reasonable to regard PBMAs as supportive foods that can help consumers move away from high-meat diets, while whole plant foods remain central to health-promoting dietary guidance. Table 7 qualitatively compares the three food groups.

Limitations and research gaps

Limitations of the evidence base

Most evidence on health effects comes from short-term interventions, observational studies, modeling, or animal experiments, which cannot capture chronic disease outcomes [47]. Several key studies involved industry support, for example, SWAP-MEAT and the

gut microbiota study that used manufacturer-supplied products [31], so independent research and transparent funding are needed. Product formulation varies greatly, and amino acid profiles differ even among products using the same protein source, making it difficult to generalize findings or set uniform guidelines. Most studies derive from Europe, North America, and other high-income settings [25], and consumer research outside the West is scarce. Regulatory and labeling research remains limited [43], and PBMA-specific data on food safety, fortification variability, and affordability in low- and middle-income countries are scarce. Differences in product formulation, serving size, and analytical methods further limit comparisons of nutritional data between studies. We need to better understand the bioavailability of nutrients like protein, Fe, and Zn [19], the independent effect of ultra-processing compared with plant-based composition, and the impact of processing energy and supply-chain complexity on sustainability assessments. This review also has limitations: it is narrative rather than systematic, did not formally assess risk of bias, and covers a rapidly evolving field.

Future research priorities

Future research and development efforts should focus on long-term randomized trials and cohort studies across a range of commercially available products; independent, transparent funding; consistent nutrient profiling and assessment; low- and middle-income country populations; PBMA-specific food safety assessment; and fortification and reformulation strategies with standardized nutrient profiles. This work would help inform evidence-based dietary guidelines and policy.

Conclusions

Ultra-processed PBMAs have become widely available as consumers seek healthier, more sustainable, and more ethical diets. Compared with red and processed meat, they can offer lower saturated fat, no animal-derived cholesterol, more fiber, and lower environmental impact. However, many are ultra-processed (though this varies by formulation); many exceed recommended salt levels; protein quality and micronutrient adequacy vary markedly; food safety and affordability (especially in low- and middle-income countries) remain understudied; and evidence on long-term health effects is limited and partly industry-funded. Current evidence supports PBMAs as transitional foods that can help people reduce meat intake, not as permanent replacements for minimally processed whole plant foods such as legumes, nuts, seeds, grains, and vegetables. We should judge their health value not by processing, but by formulation quality, frequency of consumption, dietary context, accessibility, and regulation. Whole-plant foods should remain the cornerstone of sustainable diets, supported by balanced dietary guidance, product reformulation, clear labeling, effective regulation, and evidence-based public health policy.

Acknowledgment

None

Conflicts of Interests

The authors share no competing interests in the preparation of this manuscript.

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