



Plant-Based Meat: A Review

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Abstract

Plant-based meat (PBM) describes foods made mainly from plant ingredients and designed to reproduce some of the sensory, functional and cooking qualities of conventional meat. Interest in these products has increased alongside concerns about food production's environmental footprint, animal welfare, changing dietary patterns and the need for more diverse protein sources. Advances in protein fractionation, extrusion, shear-cell processing, binding systems, flavour development and fat structuring have made it easier to produce plant-based burgers, mince, sausages, nuggets and whole-cut analogues. Even so, plant-based meat is not one uniform nutritional or technological category: its composition varies substantially according to the protein source, degree of processing, added fats, sodium, micronutrient fortification and manufacturing method. Products can provide dietary fibre and may contain less saturated fat than some meat products, but they can also be high in sodium and may provide less vitamin B12, iron or protein per serving unless specifically formulated. Many plant-based products have been found to offer environmental advantages, although the scale of those benefits depends on ingredients, energy use, processing, packaging and the animal product being replaced. Consumer acceptance remains closely linked to flavour, texture, price, familiarity, cooking performance and trust in ingredient lists. This review brings together research from roughly the past decade on the principal ingredients, processing technologies, nutritional and safety considerations, environmental implications, consumer acceptance and future directions of plant-based meat. Overall, PBM is most likely to contribute to more diverse food systems when development gives equal attention to sensory quality, nutritional adequacy, transparent communication and life-cycle assessment rather than treating meat imitation alone as the primary goal.

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Introduction

Meat features in many diets because it supplies protein and several micronutrients, while its flavour, texture and versatility in cooking are familiar to many people. However, the environmental effects of livestock production, animal-welfare concerns and growing interest in plant-rich diets have all helped drive the search for alternative protein foods. Plant-based meat (PBM), also described as plant-based meat alternatives or meat analogues, is one approach: plant ingredients are processed and combined to create products that resemble selected characteristics of meat, including appearance, bite, juiciness, aroma and cooking behaviour (Andreani *et al.*, 2023; Sha & Xiong, 2020)^[2, 9]. The modern PBM category differs from traditional plant-protein foods such as tofu, tempeh, seitan and pulses served in their familiar forms. Those foods can replace meat in a meal without imitating it. In contrast, many commercial PBM products are deliberately designed to resemble burgers, mince, sausages, nuggets or chicken pieces. The distinction is important: these products are intended not only to supply protein but also to reproduce the structure and sensory qualities people expect from meat. The development of such products draws on food chemistry, protein science,

process engineering, sensory science and nutrition. The term PBM includes a wide range of products, from relatively simple legume patties to highly formulated products made from protein concentrates or isolates, oils, binders, flavourings, colour ingredients and micronutrients. For that reason, findings about one product should not be assumed to apply to the entire category. Andreani *et al.* (2023) ^[2] emphasize that products differ in processing, nutritional composition, environmental implications and social acceptance. Similarly, El Sadig and Wu (2024) ^[5] report considerable variation in nutritional profiles and caution that the long-term health evidence for these products remains limited.

This review considers research from approximately the last ten years, focusing on ingredients, processing, product quality, nutrition, safety, sustainability and consumer-related challenges. It aims to provide a balanced overview of the potential of plant-based meat, while identifying limitations that must be addressed for it to make a useful contribution to future food systems.

Scope and Approach of the Review

This narrative review draws mainly on peer-reviewed research and review articles published between 2016 and 2026. Literature was considered on plant protein sources, meat-analogue formulation, structuring technologies, nutritional quality, food safety, environmental assessment and consumer acceptance. Recent reviews were used to map major themes, while individual studies and life-cycle assessments were considered where relevant. The material is organized by theme rather than presented as a formal systematic review: it does not claim exhaustive database coverage, a preregistered protocol or quantitative meta-analysis. As a result, the findings should be interpreted as a critical synthesis of selected recent literature, not as a systematic estimate of all available evidence.

Ingredients and Protein Sources

Soy, Pea and Other Legume Proteins

Soy protein is common in meat analogues and is available as flour, concentrate, isolate and textured vegetable protein. Its functional properties help retain water, form gels and develop fibrous structures during extrusion. Soy also has a relatively well-balanced essential amino-acid profile compared with many individual plant proteins. However, soy can be unsuitable for people with soy allergy, and its characteristic beany notes may require control through raw-material selection, processing and flavour formulation.

Pea protein has become an important alternative because it is not a major allergen in the same way as soy for many consumers, has useful protein content and can be blended with other ingredients. How well it performs depends on the crop variety, extraction method, protein composition and degree of denaturation. Pea proteins may contribute earthy or green notes and can show solubility or textural limitations under some processing conditions. Other legumes, including faba bean, lentil, chickpea and mung bean, offer opportunities to diversify raw materials and regional supply chains. Their use can also connect product development to locally grown crops, although functionality and flavour must be evaluated for each source (Sha & Xiong, 2020; Andreani *et al.*, 2023) ^[9, 2].

Wheat, Cereal and Oilseed Proteins

Wheat gluten is valued for its viscoelastic properties and ability to form cohesive, fibrous structures. It can improve bite and elasticity in products such as seitan-style analogues and can be blended with legume proteins to adjust texture. Its main limitation is that it is unsuitable for people with coeliac disease or wheat allergy, and its amino-acid profile is relatively low in lysine. Cereal proteins from oats, rice and other grains may contribute complementary functional properties but often require blending to achieve desired protein quality and structure.

Oilseed proteins, including those from canola, sunflower and other crops, are being explored as additional ingredients. These materials may provide useful protein and help diversify ingredient sourcing, but extraction can affect flavour, colour, functionality and cost. The use of side streams from oil processing or other food industries may improve resource efficiency if food safety and consistent quality are maintained. Across all these options, ingredient choice should reflect the product being made, supply and cost, allergen control, taste and texture, nutritional value and environmental impact—not protein content alone.

Blends, Fats, Binders and Minor Ingredients

Commercial formulations commonly combine more than one plant protein. Blending can improve amino-acid balance, reduce off-notes or modify hydration, gelation and fibrousness. Added fats are important because fat affects lubrication, juiciness, flavour release and heat transfer during cooking. Vegetable oils are frequently used, but liquid oils do not behave exactly like the solid or semi-solid fat found in animal tissues. Researchers and manufacturers therefore investigate structured oils, emulsions, gels and encapsulated fats to better reproduce fat distribution and reduce oil loss during cooking.

Binders and hydrocolloids can improve cohesion, water retention and cooking yield. Starches, methylcellulose, gums, fibres and other ingredients may be used depending on product design and local regulations. Colour ingredients may help create a raw-meat-like appearance or a browned cooked surface; flavour systems can contribute roasted, savoury or grilled notes. These ingredients can be technologically useful, but long ingredient lists may reduce consumer confidence. Clean-label development is therefore an important challenge: reducing additives without sacrificing safety, stability, texture or affordability requires formulation and process innovations (Andreani *et al.*, 2023) ^[2].

Processing Technologies for Meat-Like Structure

Texturization and Extrusion

Plant proteins do not naturally reproduce the muscle-fibre structure of meat. Processing is used to unfold, align and aggregate proteins into structures that provide a fibrous bite. Extrusion is one of the most established technologies. In extrusion, a hydrated mixture is conveyed through a barrel where heat, pressure and mechanical shear modify the protein matrix. On leaving the die, the material may expand or cool, depending on process design and moisture content. Low-moisture extrusion produces dry textured protein that can be rehydrated before use, whereas high-moisture extrusion can produce a moist fibrous product that more closely resembles the texture of cooked meat.

The quality of extruded material depends on moisture, temperature profile, screw configuration, residence time, shear, feed rate and cooling conditions. Protein source and the interaction of protein with starch, fibre and fat also influence the resulting structure. High-moisture extrusion is particularly attractive for producing aligned fibres, but achieving consistent anisotropy—different properties along different directions—remains challenging. Differences in protein solubility, denaturation and aggregation can lead to a product that is too soft, rubbery, dense or insufficiently fibrous. Recent work continues to focus on process optimization and on matching the properties of different protein ingredients to the equipment and product objective (Aghagholizadeh & Amiri Rigi, 2025) ^[1].

Shear-Cell Processing and Alternative Structuring Methods

Shear-cell processing uses controlled shear and temperature to organize protein-rich materials into layered or fibrous structures. It may provide an alternative to extrusion for some formulations, particularly where process control and structural alignment are important. Freeze structuring, spinning, 3D printing and other emerging approaches are also being explored. Each method has different requirements for raw materials, throughput, energy, equipment and scale-up. A method that performs well at laboratory scale may not necessarily be economically or environmentally competitive at industrial scale.

Technology should be selected according to the target food. A minced or burger product does not require the same degree of directional fibre structure as a whole-cut steak analogue. For comminuted products, binding, moisture retention and cooking yield may matter more than long fibres. Whole-cut analogues require a more complex organization of protein and fat phases. Thus, technology selection should begin with a clear product specification and sensory target rather than an assumption that maximum meat-like fibrousness is always desirable (Sha & Xiong, 2020; Aghagholizadeh & Amiri Rigi, 2025) ^[9, 1].

Flavour, Colour and Cooking Performance

Flavour is a major determinant of acceptance. Plant proteins can carry beany, grassy, bitter or astringent notes, while conventional meat flavour develops through reactions involving amino acids, sugars, lipids and heat. PBM developers use raw-material selection, fermentation, enzymatic treatment, masking agents and added flavour systems to reduce undesirable notes and build savoury character. The aim is to create flavour that is appealing across cooking methods without relying on excessive salt or complex flavouring systems.

Colour must also change in a credible way during cooking. Some ingredients are used to approximate the red or pink appearance of raw meat and the brown colour associated with cooking. However, colour changes need to match actual cooking and safety requirements; visual browning alone cannot confirm that a product has reached a safe internal temperature. Cooking performance is influenced by moisture release, fat melting, shrinkage, surface browning and structural integrity. These attributes should be tested under realistic consumer cooking conditions, not only in laboratory texture measurements.

Nutritional Quality and Health Considerations

Protein Content and Amino-Acid Quality

Protein is often the primary nutritional reason for choosing a meat analogue. However, protein quantity and protein quality are not interchangeable. Products differ in total protein per serving, essential amino-acid composition, digestibility and the effects of processing on protein availability. Soy generally provides a relatively balanced amino-acid profile, while some cereal proteins are limited in lysine and some legume proteins may be relatively lower in sulphur-containing amino acids. Combining complementary plant proteins can improve the overall amino-acid profile, although the benefit depends on the blend proportions and serving size. Protein extraction and texturization can alter protein structure and its interaction with other ingredients. Processing may improve some functional characteristics while reducing accessibility to digestive enzymes in other circumstances. Boachie *et al.* (2025) ^[3] discuss the possibility that processing-induced interactions and complexes may affect digestibility and amino-acid bioavailability. This does not mean that plant-based meat is inherently poorly digested; rather, they indicate that protein quality should be assessed in the finished product using appropriate methods and not inferred from raw ingredient data alone.

Fat, Sodium, Fibre and Micronutrients

Many PBM products contain less saturated fat than some comparable meat products, particularly products made with unsaturated vegetable oils. Plant-based formulations may also provide dietary fibre, which is absent from unprocessed animal muscle. Nevertheless, these benefits are not universal: fat content varies, and some products can contain considerable amounts of saturated fat depending on the ingredients used. Sodium may be high because salt contributes flavour, preservation and functional effects. Product comparison should therefore consider the full nutrition label, serving size and the meat product being replaced. Micronutrient composition also varies. Meat can provide vitamin B12, highly bioavailable iron and zinc. Plant ingredients do not naturally provide reliable amounts of vitamin B12 unless fortified, and iron bioavailability can be affected by the plant matrix and compounds such as phytate. Some PBM products are fortified with iron, zinc or vitamin B12, but fortification levels and nutrient forms differ. El Sadig and Wu (2024) ^[5] caution that some products may contain less vitamin B12 and iron, and that vulnerable groups need to pay attention to dietary adequacy when making substantial substitutions.

A product should not be considered healthy simply because it is plant-based, nor should all products be dismissed because they are processed. Nutritional evaluation should examine energy density, protein, saturated fat, sodium, fibre and relevant micronutrients in the context of the overall diet. PBM may function as a convenient transitional option for people reducing meat intake, but minimally processed plant foods—such as pulses, nuts, seeds and whole grains remain important components of a balanced diet. Evidence about the long-term health effects of regularly consuming newer PBM products is still developing (El Sadig & Wu, 2024) ^[5].

Antinutritional Factors and Digestibility

Plant ingredients may contain phytates, tannins, trypsin inhibitors and other compounds that can influence mineral

absorption or protein digestion. Their presence and effects depend on the crop, fractionation method and processing conditions. Soaking, heating, fermentation, germination and other treatments can reduce some antinutritional factors, but the effectiveness varies. Commercial protein concentrates and isolates may have lower or different levels of these compounds than whole flours. Further studies should assess bio accessibility and digestion in the final food matrix, because ingredient-level measurements may not fully represent the product after extrusion, cooking and consumption.

The gastrointestinal fate of meat analogues is an important research area. Formulation, protein structure, fibre, fat and heat treatment can influence digestion and nutrient release. The review by Plant-based meat analogs: A review with reference to formulation and gastrointestinal fate highlights that this evidence base remains incomplete and that ingredient functionality and processing may shape digestion outcomes (see Kumar *et al.*, 2022, in the reference list)^[7]. Well-designed human studies are needed before making broad claims about health benefits or harms.

Food Safety, Quality Control and Regulation

PBM products must meet the same fundamental expectations for hygienic manufacture and safe consumption as other prepared foods. Risks depend on ingredients, processing, handling, packaging and storage. Dry protein ingredients can carry microbial hazards if poorly controlled, while high-moisture products may support microbial growth unless appropriately processed and refrigerated or frozen. Post-process contamination, inadequate cold-chain control and incorrect cooking or storage can also compromise safety. Hazard analysis, supplier approval, environmental monitoring, validated thermal processing and clear storage instructions are therefore essential. Allergen management is especially important because common ingredients include soy and wheat, and other products may contain pea or additional legumes. Cross-contact can occur in facilities that handle multiple ingredients. Accurate ingredient lists and allergen declarations are needed, and manufacturers should validate cleaning and segregation procedures. Product labels should communicate storage conditions, cooking instructions and nutritional information clearly. Regulatory definitions and permitted names vary across jurisdictions; companies must comply with local requirements and avoid claims that could mislead consumers about ingredients, nutritional equivalence or environmental benefits.

Quality control should cover microbiological safety as well as physical and sensory properties. Relevant measures include moisture, water activity, protein and fat composition, sodium, cooking yield, texture, colour, oxidation, package integrity and shelf life. For products intended to imitate meat, cooking tests should assess shape retention, juiciness, aroma and texture under standardized conditions. Consistent raw materials and validated process controls are critical because plant protein functionality can vary with cultivar, season and supplier.

Environmental Sustainability

Environmental performance is one of the main arguments for developing plant-based meat. Life-cycle assessments generally find that many plant-based products can have lower greenhouse-gas emissions and land-use requirements than comparable products from ruminant livestock. The results

nevertheless vary with the animal product used for comparison, the crop ingredients, agricultural practices, energy mix, processing intensity, packaging and transport. It is more accurate, then, to describe environmental advantages as product- and system-dependent than to assume every plant-based product has the same footprint. Plant-based meat can reduce reliance on livestock production, but its sustainability depends on responsible sourcing and manufacturing. Protein isolates may require substantial processing, and high-moisture extrusion, refrigeration, freezing and distribution all consume energy. If ingredients are sourced from distant supply chains or linked to land-use change, benefits can be reduced. Conversely, using crops suited to local growing conditions, renewable energy, efficient water use and food-industry side streams may improve performance. Andreani *et al.* (2023)^[2] emphasize the need to consider environmental, technological, nutritional and social dimensions together.

Life-cycle assessment should compare products on a consistent functional basis. Comparing one kilogram of plant-based product with one kilogram of meat may be useful for some purposes but may not reflect differences in protein content, energy, micronutrients or typical portion size. More informative comparisons can include nutrient-adjusted or meal-based scenarios, while acknowledging uncertainty in the methods. Claims such as “sustainable” or “low carbon” should be supported by transparent, relevant evidence and should specify the boundary and comparison used. Agricultural diversification is another opportunity. Pulses can contribute to crop rotations and may improve soil nitrogen management, depending on the farming system. Developing markets for faba bean, lentil, chickpea and other regional crops could diversify protein supply and create value for local producers. However, demand must not encourage unsustainable monocultures or displace other important land uses. The most credible sustainability strategy combines appropriate ingredients, efficient processing, transparent assessment and a wider shift toward balanced, resource-conscious diets.

Consumer Acceptance and Market Challenges

A product can perform well technically and still struggle to find a market. Consumers evaluate PBM through taste, texture, aroma, appearance, price, convenience, cultural fit and perceived healthfulness. Familiarity and repeated exposure can influence acceptance, while negative expectations about processing or artificial ingredients may discourage trial. Andreani *et al.* (2023)^[2] note that consumer acceptance remains a major issue even as products have become more widely available. The product must perform well in the meal and cooking context in which it is intended to be used. Price is a practical barrier. Protein isolates, flavour systems, specialized equipment and cold-chain requirements can increase production costs. Scale, supply-chain maturity and formulation choices may reduce costs, but affordability should be considered from the beginning rather than after product development. In markets where consumers commonly prepare traditional dishes from fresh ingredients, a plant-based product may need to compete not only with packaged meat but also with low-cost pulses, tofu, paneer or home-cooked foods.

Consumer messaging should avoid assuming that all buyers are motivated by the same values. Some may prioritize environmental impact or animal welfare; others may want

convenience, variety, nutrition or simply an appealing product. Clear labels, accessible ingredient information, realistic health claims and transparent sustainability communication can help build trust. Products that are framed as one option within a diverse diet may be more approachable than those presented as a complete replacement for all meat or as automatically superior in every respect. Sensory research should include a broad range of consumers and cooking practices. Acceptance tests should examine not only liking scores but also purchase intent, willingness to pay, repeat-use intentions and reasons for rejection. In addition, studies should distinguish between blind tasting and branded tasting because expectations can influence sensory judgments. For food manufacturers, iterative product testing and feedback from consumers, chefs and retailers can identify whether the limiting factor is flavour, texture, price or perceived nutritional value.

Challenges and Future Research Directions

A number of connected challenges still need to be addressed. First, plant proteins vary substantially in functionality, and one ingredient rarely delivers all desired properties. More work is needed on blends, protein fractionation and processing conditions that create consistent structures with acceptable flavour. Second, fats must be designed to provide juiciness and flavour release while maintaining desirable fatty-acid profiles and limiting oil loss. Third, flavour development should reduce off-notes and improve cooked aroma without excessive sodium or overcomplicated formulations. Fourth, nutritional quality should be integrated into product design. Manufacturers can evaluate protein quantity and quality, sodium, saturated fat, fibre and micronutrient fortification together. The goal should be an appropriate nutritional profile for the intended role of the food, rather than simply matching the appearance of meat. Fifth, more research is required on digestibility, mineral bioavailability and the long-term effects of regular consumption. Well-designed human studies and transparent reporting of formulation details are needed to move beyond assumptions based on ingredient lists or short-term surrogate outcomes.

Sixth, sustainability assessments should use transparent assumptions and consider agricultural production, ingredient processing, energy, packaging, refrigeration, food waste and nutritional function. Product developers should also consider affordability and access. A technologically sophisticated product that is too expensive for most consumers may have limited impact on dietary patterns. Locally appropriate crops, regional processing infrastructure and partnerships with farmers could improve resilience and market relevance. Finally, innovation should extend beyond copying animal meat. Plant-based foods can be designed around the strengths of plant ingredients, including fibre, legumes, herbs, whole grains and culturally familiar flavours. Hybrid approaches and less-processed options may also play a role, depending on consumer preferences and regulatory context. Research priorities include robust sensory methods, improved texture and fat structuring, allergen management, life-cycle assessment, nutrient bioavailability, shelf-life optimization and studies of actual purchasing and eating behaviour. Collaboration among food scientists, nutritionists, engineers, farmers, regulators and consumers will be important.

Conclusion

Plant-based meat has developed from relatively simple textured protein foods into a diverse category of products designed to reproduce selected properties of conventional meat. Advances in plant protein ingredients, extrusion, shear-based structuring, flavour design and fat systems have expanded the range of possible products. These technologies create opportunities to diversify protein supply and may reduce environmental impacts when compared with some animal-derived products, particularly when ingredient sourcing and manufacturing are managed responsibly. However, plant-based meat should not be treated as a uniform category or assumed to be nutritionally superior in every case. Protein quality, sodium, saturated fat, micronutrient fortification, digestibility, processing and environmental performance vary by formulation. Sensory quality, price, cultural relevance and consumer trust remain central to adoption. The future of PBM should not be judged only by how closely it imitates meat. Its value will also depend on whether it tastes good, offers suitable nutrition, is safe and affordable, and delivers environmental benefits that can be demonstrated. Continued research and transparent evaluation will be necessary for plant-based meat to contribute meaningfully to sustainable and healthy food systems.

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