



Plant-based Meat Analogs: Perspectives on Their Meatiness, Nutritional Profile, Environmental Sustainability, Acceptance and Challenges

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Accepted: 2 September 2024 / Published online: 28 September 2024

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Abstract

Purpose of Review Plant-based meat analogs (PBMA) have been the subject of interest over the past few years due to consumers' demand for environmentally friendly, healthful, and non-animal-based foods. A better comprehension of the composition, structure, texture, nutrition, and sustainability of these PBMA is necessary.

Recent Findings This review articulates the protein sources and composition of PBMA and their “meatiness” with respect to texture, structure, and flavor enhancement. The components used in the analogs, such as unsaturated fats, fibers, vitamins, minerals, carbohydrates, and plant-based oils enriching their nutritional profile, are described. The study identifies the environmental and sustainability impact of PBMA, as crucial to the survival and maintenance of biodiversity.

Summary More studies are warranted to scope and underscore the significance of the analogs and comprehend the texture or structure-function relationships. Further product development and testing thereof may ultimately result in quality meat analogs that respect meat taste, health and acceptance of consumers, environmental sustainability, animal welfare, and current challenges.

Keywords Plant-based meat analogs · Hydrocolloids · Nutritional profile · Plant-based protein sources · Environmental sustainability · Consumer acceptance

Introduction

Plant-based meat analogs (PBMA), often simply called plant-based meats or meat substitutes, are food products designed to replicate the taste, texture, and appearance of

animal-based meat, but using plant-derived ingredients. These products have gained popularity in response to various concerns, including health, sustainability, and ethical considerations associated with conventional meat production [1, 2]. The ingredients of PBMA include various protein

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sources including soy, peas, wheat (gluten), and other legumes [3]. These proteins are processed to mimic the fibrous and chewy texture of meat. There are also plant-based fats used such as coconut and canola oil, and flavor enhancers like yeast extracts, miso, mushrooms, and spices. These ingredients are often used to replicate the mouthfeel and juiciness of meat to provide a savory and umami-rich flavor [4, 5]. Maillard browning reactions may also be encouraged to result in a more complex flavor profile.

The texture and structural reconfigurations of these PBMA are crucial to understanding their potential and use in the food industry. However, achieving a texture similar to traditional meat is a significant challenge. In light of this, extrusion has become a common processing method often used to create the desired fibrous structure [6–8]. Additionally, ingredients including starches, fibers, and hydrocolloids contribute to the texture. However, not only is the desired texture required but PBMA are developed to provide a nutritional profile similar to traditional meat, with a focus on protein content. These products are often fortified with vitamins and minerals such as B12, iron, and zinc, whereas some PBMA also incorporate fiber, making them nutritionally diverse [9–11]. They are generally perceived by consumers as healthier alternatives to traditional meat due to a lower saturated fat and cholesterol content [132]. Given the widespread use of flavor enhancers, it is essential to consider factors such as sodium levels and overall ingredient quality [12, 13]. In this review, we look at the protein sources and composition of PBMA followed by their “meatiness” (in terms of texture, structure, and flavor) and nutritional profile. The environmental sustainability of PBMA is mentioned. Thereafter, their acceptance and challenges are discussed. For this review, academic search engines were used including Google Scholar, Web of Science, Scopus, PubMed Central, BASE, Semantic Scholar, and CORE. Keywords like “plant-based meat analogs”, “hydrocolloids”, “nutritional profile”, “plant-based protein sources”, “environmental sustainability”, and “consumer acceptance” were also used.

Protein Sources and Composition of PBMA

PBMA are commonly produced using plant-derived proteins from soy, wheat, peas, and other legumes. Research focuses on optimizing the protein composition to mimic or replicate the taste and texture of traditional meat products. According to the literature as described in Table 1, soy-based products like soybeans and soy protein isolate were the most utilized protein sources in the meat analogs, followed by peas and pea protein. Soy protein is a popular choice for PBMA due to its versatile nature and relatively high protein content. It can be processed into various forms, including soy protein isolate (SPI) and soy protein concentrate (SPC).

Table 1 Main ingredients in meat analogs based on literature

Categories	Protein source	Fat source	Other food additives	References
Burgers, Cold Cuts, Cutlets, Meat Balls	Soy, Soy derivatives, Rice, Oats and Buckwheat	Seed Oil and Olive Oil	Modified Starch, Citric Acid, Flavou-ring and Coloring	D’Alessandro et al. [22]
Burgers, Minced, Chicken Nuggets, Chicken Cutlets, Seafood, Sausages, Cold Cuts	Soy, Gluten (Wheat), Pea Protein, Isolated Soy, and Pea Proteins	Unspecified vegetal fat, Soy Oil, Sunflower Oil, Cottonseed Oil, Coconut Fat, Coconut Oil	Methylcellulose, Xanthan Gum, Gel-lan Gum, Carrageenan Gum	Romão et al. [23]
Various	Soy, Wheat, Starch (Potato and Corn), Pulses, and Oats	N/A	Gellan gum, locust bean gum, guar gum, carrageenan, xanthan gum, methylcellulose, mono and diglyc-erides of fatty acids, mono and di-acetyl tartaric acid, esters of mono and diglycerides, calcium stearoyl lactate	Mariseva et al. [24]
Burgers, Sausages, Minced, Chicken, Cutlets, Seafood, Others,	Soy Protein, pea protein, soybeans, hydrolyzed vegetable protein, myco-protein, almonds	Vegetable oil, canola oil, sunflower oil, sunflower kernels, rice bran oil, coconut oil, flax seed meal, cocoa butter, peanuts	N/A	Curtain et al. [25]

Source: [13]

Specifically, soy protein/ingredients in the likes of soy flour, concentrate, and isolate are incorporated into meat analogs due to their excellent technofunctional properties including emulsification, gelation, and fat and water-holding capacities [14]. The flour form is not as extensively processed as the protein form, although many types of soy flour exist commercially, which include toasted, defatted, and full-fat, among others. The concentrate and isolate forms have richer protein contents and are the products of defatted soy flake fractionation [15, 16]. Soy protein isolate (SPI, 90% protein) is produced following alkaline extraction and acidic precipitation whereas soy protein concentrate (SPC, 70% protein) can be obtained through aqueous alcohol extraction. Regarding their use in meat analogs, SPI has a much better protein purity on a dry basis, a lighter color, and a bland flavor in comparison with other soy products. However, PBMA do not require a high rate of protein purity [17]. Furthermore, other components in the matrix potentially add additional nutrients to the analogs during production.

Wheat and pea proteins are other common protein sources used in PBMA. They provide elasticity and texture, making them suitable for products like seitan [18]. Wheat gluten naturally forms thin protein films when elongated and readily transforms into fibrous materials, characteristically resulting from its molecular and mesoscopic properties [14]. Wheat gluten is characterized by a disulfide protein linkage which enables its formation of a three-dimensional network, rendering it a crucial fibrous component of structural configurations [19, 20]. Pea protein is gaining popularity for its neutral flavor profile and high protein content. It is often used in combination with wheat or other proteins to improve the overall amino acid profile [21].

Also, apart from the presence of gluten from wheat as the protein source, pulses are generally more frequently used than grains [13]. Proteins from various legumes, such

as lentils, chickpeas, and fava beans, can also be added to enhance the nutritional profile and texture of PBMA [26]. Leguminous proteins derived from lupine, peas, chickpeas, lentils, and various other bean types have been studied for their gelling, foaming, emulsifying, and other technofunctions [27, 28]. Pea protein stands out among them all for potential use in meat analogs. A structural analysis of pea protein using high-moisture extrusion suggests that pea-based structures are softer than soy-based products, leading to further studies on their gel strength enhancement [29]. The hydrogen-protein bond could be modified using salts/chaotropic ions for instance, or the processing conditions like protein size, temperature, and so on could be optimized [30, 31]. It is possible that certain pretreatment and processing steps including fractionation processing of legumes would affect their network/structure-forming behavior.

Similar to animal sources, legumes like soybeans and peas have high protein content. A comparison of the protein and essential amino acid (EAA) profile of the different legume and grain protein sources of PBMA, compared to beef and chicken is presented in Table 2. Even though grains like quinoa and oats are lower in protein, they are still beneficial when included in a varied protein diet. For EAAs, the high lysine levels of soybeans and peas contrast with the low lysine content of cereals like wheat and rice. Compared to legumes, grains, such as wheat gluten, have a greater methionine concentration. Although beef and chicken are great providers of these vital amino acids, significant levels could also be found in legumes and grains. A good source of valine is legumes, such as peas and soybeans. Legumes and cereals both contain sufficient amounts of threonine but in different proportions. Among other foods, soybeans are especially high in tryptophan. By integrating different grain and legume sources, PBMA can efficiently satisfy key amino acids and protein requirements. Because of their high

Table 2 The total protein and essential amino acid profile of different legume and grain sources of protein in PBMA compared to beef and chicken

Food Source	Protein (g/100 g)	Lysine (g/100 g)	Methionine (g/100 g)	Leucine (g/100 g)	Isoleucine (g/100 g)	Valine (g/100 g)	Threonine (g/100 g)	Tryptophan (g/100 g)	Phenylalanine (g/100 g)
Beef (ground)	26.0	1.7	0.7	1.7	1.0	1.1	1.0	0.3	1.1
Chicken (breast)	31.0	2.1	0.9	2.4	1.4	1.3	1.2	0.3	1.2
Soybeans	36.5	2.7	0.5	2.5	1.6	1.8	1.7	0.6	2.0
Peas	25.0	1.8	0.2	1.8	1.1	1.2	1.0	0.2	1.3
Lentils	25.8	1.8	0.2	1.8	1.0	1.1	1.0	0.2	1.2
Chickpeas	19.0	1.5	0.2	1.6	0.9	1.0	0.8	0.1	1.1
Quinoa	14.1	0.8	0.4	0.8	0.5	0.6	0.6	0.1	0.6
Brown Rice	7.5	0.3	0.2	0.6	0.3	0.4	0.3	0.1	0.5
Oats	16.9	0.7	0.3	1.0	0.7	0.8	0.6	0.2	1.1
Wheat Gluten	75.0	0.7	1.1	6.0	3.3	4.2	2.9	0.3	4.5

Sources: [133–135]

protein and lysine content, soybeans and peas are especially beneficial. A thoughtful combination of grains and legumes can provide plant-based meat substitutes that are nutritionally complete, even though no single plant source can precisely replicate the amino acid profile of beef and chicken. This strategy addresses nutritional requirements as well as sustainability goals.

Likewise, rice protein is a hypoallergenic option that is often used in combination with other plant proteins to achieve a balanced amino acid profile in PBMA s [32]. Some fungal proteins are also used when designing plant-based protein components of PBMA s. An example of this is mycoprotein, derived from the naturally occurring fungi *Fusarium venenatum*. Fungal-derived protein has a fibrous texture and is the key ingredient in products such as Quorn [33–35]. These protein sources are frequently combined and processed to create PBMA s that closely resemble the taste, texture, and nutritional composition of traditional meat products. The specific composition may vary among different brands and products as manufacturers experiment with different formulations to enhance the overall quality of plant-based alternatives.

Other components incorporated into PBMA s may include oilseed proteins, fats, and oils. The most common oilseed proteins used are derived from rapeseed and canola. Rapeseed consists of cruciferin and napin, known for good gelation, foam formation, and emulsifying capacity which can promote “meatiness”, especially when subjected to high pressure or heat [36, 37]. Notably, the ionic and hydrophobic interactive capabilities of napin contribute to its ability to aggregate and extend casein-containing products using salt bridges [38]. Meanwhile, the main proteins present in canola are albumins and globulins which cohesively form gels at very low salt concentrations [39]. The PBMA s known to date have low-fat contents because defatted ingredients are usually used as these affect the gelation and fibrous structure formations. For instance, the base ingredient for soy protein isolate production is defatted soy flour with less than 1% oil. The produced soy protein isolate consequently has a very minuscule amount of fat. To enhance the fat content, proteinous components like mildly fractionated soy fractions with natural fat are incorporated [17]. Oils from corn, soy, sunflower, palm, rapeseed, coconut, and canola are also used for PBMA s to enhance their volatile flavors [14]. When it comes to caloric content, plant-based meat substitutes are usually more balanced in terms of fat and protein content and have a greater proportion of carbs than traditional meats (Table 3).

Finally, some colorings may be added. These are mostly heat-stable coloring agents, including carotenes, malts, caramels, turmins, and cumins [40]. Browning agents, mostly, reducing sugars such as mannose, galactose, arabinose, maltose, dextrose, xylose, and lactose can also be used as they

Table 3 Proportion of energy from fat, protein, and carbohydrate in PBMA s compared to beef and chicken

Food Source	Energy from fat (%)	Energy from protein (%)	Energy from carbohydrate (%)
Beef (ground, 85% lean)	60	39	1 ¹
Chicken (breast, skinless)	20	80	0 ¹
Beyond burger	62	24	14 ²
Impossible burger	55	31	14 ³
Gardein beefless ground	34	42	24 ⁴
MorningStar farms Grillers	38	48	14 ⁵
Quorn meatless grounds	26	40	34 ⁶

¹**USDA National Nutrient Database for Standard Reference:** Provides nutrient profiles for various food items, including beef and chicken. USDA Database. https://agdatacommons.nal.usda.gov/articles/dataset/USDA_National_Nutrient_Database_for_Standard_Reference_Legacy_Release/24661818

²**Beyond Meat Nutrition Facts:** Beyond Burger nutrition profile. Beyond Meat. <https://www.beyondmeat.com/en-US/>

³**Impossible Foods Nutrition Facts:** Impossible Burger nutrition profile. Impossible Foods. <https://impossiblefoods.com/>

⁴**Gardein Beefless Ground Nutrition Facts:** Gardein product profile. Gardein. <https://www.gardein.com/beefless-and-porkless/gluten-free/ground-bef>

⁵**MorningStar Farms Grillers Nutrition Facts:** MorningStar product profile. MorningStar Farms. https://www.morningstarfarms.com/en_US/home.html

⁶**Quorn Meatless Grounds Nutrition Facts:** Quorn product profile. Quorn. <https://www.quorn.co.uk/>

can react with protein amine groups via the Maillard reaction, to mimic meat browning [41].

“Meatiness” of PBMA s

Texture and Structure

Achieving a meat-like texture is considered essential for consumer acceptance. PBMA s are designed to resemble the mouthfeel and texture of animal meat, including qualities of chewiness, juiciness, and tenderness. The role of different plant proteins, fibers, and other ingredients is being investigated by researchers and food scientists to replicate the fibrous, texture, mouthfeel, and appearance characteristics of conventional meat using various techniques and ingredients. Protein network formation is the first thing to consider in this regard because the primary protein source in PBMA s plays an important role in creating a texture similar to traditional meat. Thus, ingredients such as soy protein, wheat gluten, and pea protein are often used to form a protein network that gives the product its fibrous and chewy texture [42–44]. Most PBMA s include filler materials (eg. air bubbles, lipid droplets, plant tissues, or solid particulates) dispersed within

biopolymer matrices [2], as illustrated in Fig. 1A. According to Wang et al. [45], the biopolymer networks are usually assembled from polysaccharides and proteins, organized in various rheological configurations that define the final product. These structures form single, interpenetrating, phase-separated, or co-gelling networks with the functional properties of the resulting gels depending on the nature of the crosslinks between the biopolymers. These links range from hydrogen bonding to hydrophobic attraction, electrostatic bridging, and covalent bonding (Fig. 1B, 1C) [46, 47].

PBMAs with an appealing texture and structure may be made using advanced processing methods such as extrusion, texturization, and high-pressure processing. Extrusion is a common processing method for PBMAs, and it involves forcing the raw ingredients through a die under controlled temperature and pressure. This process helps align proteins and other components, contributing to the desired texture [48–50]. To obtain the appropriate texture and structure, optimal component ratios must be adjusted throughout the production process. This may involve experimenting with various adhesive agents, texturing additives, and protein-to-fat ratios to improve the mouthfeel and grinding resistance [51].

In addition to this, various texturizing ingredients are used to enhance the mouthfeel and structure of plant-based meats. These may include fibers, gums, and starches that contribute to the overall texture and help simulate the juiciness associated with traditional meat [52]. Techniques for preparing PBMAs that mimic the cooking of conventional meats, such as grilling, baking, or frying, may contribute to providing flavor compounds and improving texture [52–54]. The fat emulsion approach is also used sometimes, as fat is

a key component in traditional meat for its overall juiciness and flavor. PBMAs thus often incorporate plant-based fats such as coconut oil, canola oil, or sunflower oil to replicate the fatty mouthfeel of meat [55–58]. Some PBMAs use gelling agents or hydrocolloids to create a gel-like structure, improving the firmness and bite of the analogs. Agar, carrageenan, and konjac are examples of gelling agents used in these plant-based formulations [59–62].

In summary, the texture and structure of PBMAs involve a combination of ingredient selection, processing methods, and formulation techniques to create a product that closely mimics the texture and structural characteristics of conventional meat. Manufacturers may enhance the texture and structure of PBMAs to make them “meatier” and more appealing to customers looking for more sustainable and ethical food options. Active, ongoing research and innovation to further improve the texture and overall quality of PBMAs is evident [63, 64].

Flavor Enhancement

The challenge of PBMAs lies in replicating the complex flavors associated with meat. Researchers have explored the use of natural flavor enhancers, such as yeast extracts and specific plant-derived compounds, to improve the taste of PBMAs. The flavor enhancement of PBMAs is a key aspect of their success in the market, as consumers expect these alternatives to replicate the taste of traditional meat. Achieving a savory, umami-rich flavor profile involves a combination of ingredient selection, processing techniques, and the incorporation of natural flavor enhancers. Some key considerations in flavor enhancement include the use of umami

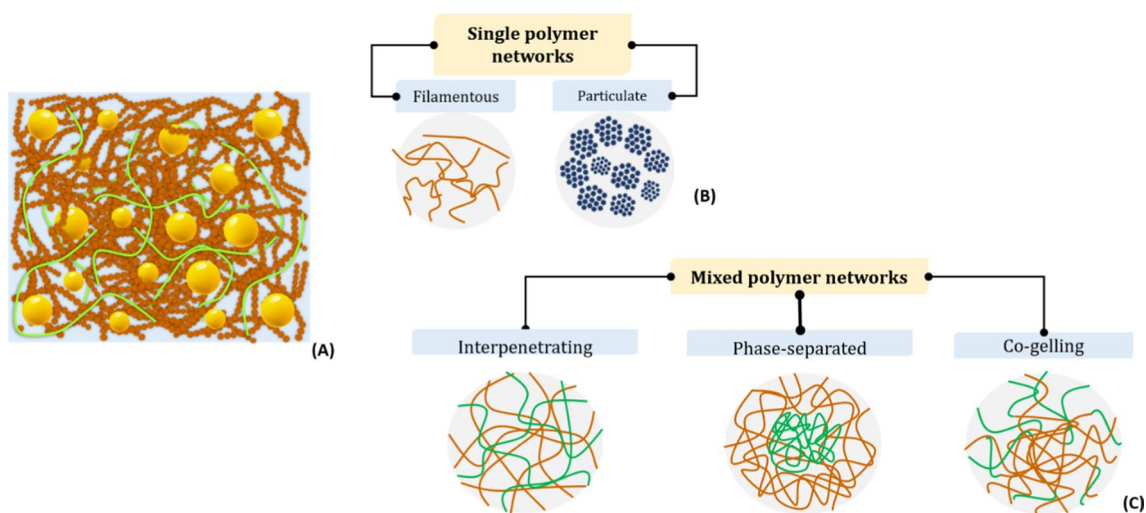


Fig. 1 Plant-based meat analogs (PBMAs) consist of fillers such as air bubbles, lipid droplets, and plant tissues inside a biopolymer network (A); The biopolymer networks in PBMAs can have different

structural arrangements depending on the number, type, and interactions of the biopolymers, which may be single (B) or mixed networks (C). Adapted from McClements [2]

components, yeast extracts, and fermented ingredients, as well as herbs and spices, smoke flavors, and Maillard reaction products. In all cases, sensory analysis, and consumer testing is important to ensure product satisfaction and competitiveness in the marketplace [4, 5, 65].

Umami, often described as the fifth taste, is associated with a savory and meaty flavor. Umami-rich ingredients such as soy sauce, miso, tomato paste, and mushrooms are used to enhance the overall flavor profile of PBMAAs [66]. Yeast extracts and fermented ingredients, such as autolyzed yeast extract or nutritional yeast, are also commonly used in plant-based meat formulations to enhance the overall savory complexity of flavors. Fermented ingredients like tamari or fermented soy products can also add depth to the taste [67–69] as can a blend of herbs and spices (e.g. garlic, onion, paprika, cumin, and black pepper) [70–72].

Smoke flavors contribute to the characteristic taste of grilled or smoked meat. Natural smoke flavoring can be derived from sources such as hickory or mesquite [72, 73]. The Maillard reaction, which occurs between amino acids and reducing sugars during cooking, contributes to the development of complex flavors [74]. PBMAAs may utilize ingredients and processing methods that promote the Maillard reaction, such as browning agents, to enhance their overall taste [6, 75, 76]. Above all, understanding consumer preferences and conducting taste tests can help manufacturers fine-tune formulations to meet the expectations of target audiences [71, 77, 78]. Thus, flavor enhancement in PBMAAs involves a combination of natural ingredients, processing techniques, and careful formulation to create a product that not only mimics the taste of traditional meat but also offers a distinctive and enjoyable eating experience for consumers.

Appearance

The visual attributes of PBMAAs, such as shape, size, color, glossiness, and transparency, are referred to as their appearance. The appearance characteristics of PBMAAs contribute to the consumer's perception of how closely the product resembles traditional meat and thus contribute to a meat-like sensory experience. PBMAAs are frequently developed to look like classic meat dishes like meatballs, sausages, and hamburgers. This entails using molding and shaping processes to produce recognizable shapes for customers. Furthermore, PBMAAs undergo the addition of external features, including browning, grill marks, and sear lines, to improve their appearance and replicate the cooking process, which adds to their "meatiness".

Color is the most significant characteristic of food appearance, especially when closely related to other components contributing to food quality. The color of PBMAAs is essential to provide a flesh-like appearance. With slight variations based on the particular product, the color should be quite

similar to cooked meat, such as dull red for hamburger patty and brown for ground beef. The required color is usually achieved by using natural coloring agents. Meat-like red, brown, pink, or yellow pigments are produced by ingredients including beetroot, annatto, caramel, and vegetable juices. The browning and color formation of PBMAAs can also be enhanced via the Maillard reaction, which occurs during cooking, thereby resulting in a more flesh-like appearance [79].

The color of PBMAAs is influenced by several factors, with the processing parameters and constituent compositions known to have the largest effects. The color potential of different protein sources varies significantly. Soy protein isolates come in a variety of colors, including cream, beige, and brown [80, 81]. The browning effect caused by wheat gluten is negligible. Browning effects are most comparable to those of meats when it comes to legume proteins, including those found in lentils or peas. Achieving the appropriate color and appearance requires a meticulous assessment of the appropriate proportions of plant materials [82]. The formulation must be optimized through modification of its ingredient ratios to improve visual attractiveness by experimenting with various protein-to-fat ratios, extrusion, and texturizing agents. PBMAAs often undergo marbling and color-matching processes to resemble traditional meat products' appearance [83–85].

Nutritional Profile of PBMAAs

Studies that have examined the nutritional composition of PBMAAs focus on the content of essential nutrients that are present in traditional meat. Nutritional concerns relate to amino acid profiles, vitamin and mineral content, and overall nutritional adequacy [86–88]. Since consumers often choose plant-based alternatives as part of a diet that aligns with health and environmental concerns, the nutritional profile of PBMAAs is an important influence on consumer acceptance and market success. The key considerations in the nutritional profile of PBMAAs include protein content and quality, fat content and type, carbohydrates and fiber, vitamins and minerals, sodium content, and cholesterol [3, 7, 75, 89–92].

Protein sources provide significant amino acids that the body needs for general health, muscular development, and repair. For vegetarians, vegans, and anybody aiming to decrease their consumption of animal products, plant proteins are an excellent alternative [89, 90]. PBMAAs are supplemented with fats to increase both omega-3 and omega-6 fatty acid nutritional content, providing a balance of saturated and unsaturated fats, and improve flavor, juiciness, and mouthfeel. The types of fats used are chosen. To enhance the nutritional profile, manufacturers use omega-3-rich components like flaxseed oil [65, 91]. Carbohydrates and fiber

contents can also vary among PBMA and reflect the plant sources used to formulate them. Some formulations may include the naturally occurring starches, fibers, and sugars found in plants, including grains, legumes, and vegetables [3, 75]. The general flavor, texture, and structure of PBMA are influenced by carbohydrates, which also supply energy. Additionally, their presence might enhance fiber content in final products. The inclusion of fiber is often considered a positive aspect, contributing to the overall satiety and health of the digestive system. Additional soluble (e.g. chicory root, oats) and insoluble fibers (e.g. psyllium husk) may be added to PBMA [7, 92] to improve texture, facilitate bowel movements, and increase satiety and fullness perceptions. PBMA that include high-fiber components respond to customer desire for diets that promote gastrointestinal health and overall health [3, 7, 75, 92].

PBMA can contribute to the intake of essential vitamins and minerals if added to levels found in traditional meat through fortification. They may be fortified using ingredients such as plant-based proteins, vegetables, and grains to provide a broad spectrum of nutrients [11]. Vitamin B12, vitamin D, iron, zinc, and calcium, are the micronutrients most frequently added during fortification processes. [9–11].

Sodium levels in PBMA can vary, and some products may contain added salt for flavor enhancement. Managing sodium content is essential for those consumers who are watching their salt intake for health reasons [12, 13, 93]. PBMA are naturally cholesterol-free, which can be beneficial for heart health and is a health-related characteristic over animal-based meats [94–96]. It is important to note that the nutritional profile of PBMA can vary between products and brands. As the industry evolves, there is ongoing research and innovation to optimize the nutritional content of these products, addressing specific health concerns and nutritional needs of consumers. Dietary preferences and nutritional requirements can be satisfied by customizing a healthy diet of PBMA. Properly established these ingredients can provide a healthy, well-rounded substitute for conventional meat products that also fit within vegetarian,

vegan, and flexitarian diets. Additionally, consumer education and awareness regarding the nutritional aspects of plant-based diets play a crucial role in the overall success and adoption of these alternatives.

Due to their ability to satisfy dietary preferences and nutritional needs while acting as substitutes to traditional meat products, PBMA have grown in popularity. Sample meal plans for vegetarian, vegan, and flexitarian diets are presented in Table 4. Dietary modelling studies that support the substitute of PBMA for meat were reported [136, 137]. When properly prepared, vegan and vegetarian meals may satisfy all dietary needs. To guarantee sufficient consumption of key amino acids and minerals, Clarys et al. [136] stressed the significance of varying protein sources, such as legumes and PBMA. In addition to drastically cutting greenhouse gas emissions, substituting plant-based meat alternatives can also enhance public health outcomes by reducing the risk of illnesses linked to nutritional deficiencies [137]. PBMA can be as nutritious as animal-based diets. Studies have shown that PBMA can supply sufficient amounts of additional minerals and EAAs [138].

Environmental Sustainability of PBMA

There has been some research on the environmental footprint of PBMA compared to traditional meat products, considering factors such as land use, water consumption, and greenhouse gas emissions, biodiversity conservation, energy efficiency, and waste management [97, 98]. The sustainability and environmental impact of PBMA are significant considerations, since these products are often promoted as more environmentally friendly alternatives to traditional meat. PBMA generally require less land compared to conventional meat production since plant-based protein sources (e.g. soy, peas, and wheat) typically have a smaller land footprint than raising livestock – and thereby contribute to the conservation of natural ecosystems and reduce deforestation [97, 98].

Table 4 Example meal plans for PBMA in vegetarian, vegan, and flexitarian diets

Meal type	Vegetarian diet	Vegan diet	Flexitarian diet
Breakfast	Oatmeal with almond milk, fresh fruits, and nuts	Smoothie with spinach, banana, plant-based protein powder, and flaxseeds	Greek yogurt with granola and fresh berries
Lunch	Salad with mixed greens, cherry tomatoes, cucumbers, and grilled Beyond Burger slices	Chickpea salad sandwich with avocado on whole-grain bread	Quinoa bowl with black beans, corn, tomatoes, and a grilled Impossible Burger patty
Dinner	Stir-fried vegetables with tofu and brown rice	Spaghetti with lentil-based Bolognese sauce made using Gardein Beefless Ground	Roasted vegetables with a small portion of grilled chicken or tofu
Snack	Hummus with carrot sticks	Almond yogurt with blueberries	Apple slices with peanut butter

Sources: [139–142]

A more ecologically balanced food system may benefit from using plant-based meat substitutes, they are becoming more widely acknowledged. These meat substitutes are created completely of plant components, yet they are intended to have the flavor, texture, and nutritional composition of real meat. By analyzing their effects on the environment, economy, and society, PBMA's may be considered sustainable. Recent studies comparing plant-based meat analogs with real meat products focused on environmental impact, nutritional profile, health effects, and consumer acceptance is presented in Table 5.

Likewise, PBMA's generally have a lower water footprint compared to conventional meat products. When it comes to producing the same quantity of plant-based protein from sources like vegetables, grains, legumes, soybeans, or peas, meat production requires a much higher water footprint [98]. For instance, approximately 1,800 gallons of water are needed to produce one pound of beef from growing cattle until obtaining their beef. More volumes of water are used to irrigate the grass, forage, and feed that cattle consume

throughout their lifespan [99]. Consuming PBMA's allows people to significantly decrease their water footprint and contribute to conserving freshwater resources, both of which are essential for preventing water shortages and maintaining agricultural sustainability [100–102].

PBMA's production requires less water than producing traditional meat. For instance, one pound of beef requires around 1,800 gallons of water to produce, whereas plant-based substitutes use much less water. By using less water for agriculture, plant-based meat substitutes can help alleviate the effects of water shortage.

When compared to animal-based foods, plant-based meat substitutes are associated with far lower greenhouse gas emissions (methane and carbon dioxide) – in some cases up to up to 90% less. The methane emissions associated with livestock digestion and manure management contribute significantly to the environmental impact of conventional meat production [103–106].

Compared to traditional meat, plant-based meat analogs produce noticeably fewer greenhouse gas emissions,

Table 5 Recent studies comparing PBMA's with real meat products, focused on environmental impact, nutritional profile, health effects, and consumer acceptance

Comparison Aspect	Significant findings	References
Resource use	Meat analogs require significantly less water and land resources than traditional meat	Eshel et al. [109]
Life cycle assessment	Plant-based meat analogs have lower environmental impacts across multiple categories compared to beef	Smetana et al. [143]
Health benefits & climate change	Dietary change to plant-based proteins can improve health outcomes and reduce climate impact. Plant-based diets associated with lower risks of heart disease, diabetes, and certain cancers.	Springmann et al. [137]
Diet and sustainability	Plant-based diets associated with lower environmental impacts and better health outcomes	Aleksandrowicz et al. [144]
Consumer Willingness to Pay	Consumers willing to pay a premium for plant-based meats perceived as healthier and more sustainable.	Lusk et al. [104]
Greenhouse Gas Emissions with Carbon footprint	Plant-based foods generally have a lower carbon footprint compared to animal-based foods. Meta-analysis confirmed significantly lower emissions for plant-based meats compared to animal-based products.	Clune et al. [145].
Environmental impact	Plant-based proteins can reduce emissions by up to 90% compared to beef; use 45%-99% less land	Poore & Nemecek [97]
Global health and sustainability	Adopting plant-based diets can contribute to global health improvements and sustainability	Willett et al. [146]
Health Perceptions	Plant-based meat perceived as healthier by consumers, but nutritional knowledge gaps exist.	Siegrist & Hartmann [147]
Consumer acceptance	Increasing consumer acceptance of plant-based meats as taste and texture improve	Tziva et al. [148]
Economic aspects	Scaling up plant-based meat production can reduce costs and create economic opportunities	Rubio et al. [149]
Nutritional Profile	Plant-based meat analogs can be fortified to match the protein and micronutrient content of real meat. Differences in amino acid profiles noted.	Van Vliet et al. [150]
Market growth	Plant-based meat market grew by 27% in 2020	Good Food Institute [151]
Consumer Acceptance	Plant-based meat analogs have high acceptance among flexitarians and vegetarians, but sensory attributes need improvement for broader meat-eating population.	Tso & Forde [152]

according to a number of studies. For instance, research by Poore and Nemecek (2018) showed that, in comparison to beef, plant-based proteins can lower emissions by as much as 90%. Making the switch to plant-based meat can significantly reduce food production's carbon footprint.

By reducing the demand for animal agriculture, PBMAAs can contribute to biodiversity conservation. One of the primary drivers of habitat loss and biodiversity reduction is the increase of agricultural land used for raising livestock. Because of land conversion, deforestation, and pollution, large-scale animal husbandry frequently results in the destruction of habitats, a decline in biodiversity, and the extinction of species. Consuming proteins from plants rather than animal sources encourages biodiversity conservation and promotes sustainable land-management practices that are supportive of human sustainability as well as healthier ecosystems [107, 108]. The same quantity of protein may be produced on less land with plant-based meat substitutes than with animal products. Diets based mostly on plants consume 45–99% less land than diets containing meat [97]. Reducing deforestation and conserving natural environments can be achieved through the use of plant-based meat substitutes [143].

PBMAAs are energy efficient because they often require less energy to produce compared to traditional meat [109–112]. The energy-intensive processes associated with animal farming, including feed production, transportation, and animal husbandry, all contributing to the overall environmental impact.

Conventional cattle husbandry has a detrimental effect on biodiversity by causing pollution, overgrazing, and habitat degradation. Well-managed plant systems can alleviate these stresses.

As a result of reducing the environmental impact of food production, plant-based meat substitutes can contribute to biodiversity conservation [108].

Waste management is another hallmark of PBMAAs. When comparing PBMAAs with conventional meat production, which frequently requires the disposal of animal waste materials and by-products, PBMAAs usually produce less waste. The waste generated in conventional meat production, including bones, skin, and other by-products, can pose challenges for disposal and contribute to environmental pollution [76, 91]. Furthermore, by-products and residues may be exploited more effectively in plant-based manufacturing procedures, reducing waste production and supporting the concept of the circular economy. Notably, the sustainability of PBMAAs can vary depending on factors such as agricultural practices, supply chain management, and processing methods. Consumers and policymakers play a role in shaping a more sustainable food system by making informed choices and supporting initiatives that prioritize environmental conservation.

Acceptance and Challenges

The market for PBMAAs is rapidly expanding as more people are turning to flexitarianism, vegetarianism, and veganism. Nonetheless, the number of consumers who are willing to adopt plant-based substitutes is limited [153]. To date, despite major investments in product development, the sensory qualities of PBMAAs still do not necessarily closely mimic those of traditional meat [115]. Taste and texture remain the two major barriers that limit the consumption of PBMAAs [116].

Age, culture, income, region, gender, tradition, and education level all influence the interest of individuals in purchasing PBMAAs (See Fig. 2). Age-wise, teenagers are more motivated by issues related to accessibility and ecological impact to choose plant-based meats than older individuals (45–59 years old) who prefer flavor and familiarity. Countries with higher incomes consume large amounts of meat, and the average low-income populations tend to reduce their meat consumption [117]. It has also been shown that women are more likely than males to reduce their meat intake. Studies on whether they will consider PBMAAs or not are warranted. Health-conscious consumers were consistently identified as females over 55, whereas environmentally-concerned consumers were consistently identified as young (between the ages of 18 and 34) with predominantly high education levels [117].

A cross-country survey demonstrated that populations in India and China embrace PBMAAs more than the population of USA [86, 118]. Indian consumers demonstrated much lower meat attachment and significantly higher food neophobia compared to those in China and the USA and predictors of intake were related to sustainability, morality, importance, and enthusiasm [86, 118]. In China, the main predictors of purchasing PBMAAs were healthiness, appeal, tastiness, and sustainability, while in USA it was appeal, enthusiasm, and low disgust.

PBMAAs are bought and requested by consumers for a variety of reasons, including taste, ethics, the environment, and health. The flavor enhancement, texture, and culinary versatility of PBMAAs are becoming more widely recognized. Consumers who prefer meat-based foods but are open to alternatives find plant-based options intriguing since manufacturers have made substantial improvements in mimicking the flavor and texture of conventional meats. Besides, curiosity and an appetite for adventure lead certain customers who are prepared to explore various dishes and culinary innovations. PBMAAs provide people the chance to experiment with new and inventive plant-based cuisines and recipes, broadening their culinary horizons [119].

Plant-based meat substitutes are a solution for those who are allergic to animal proteins or have dietary

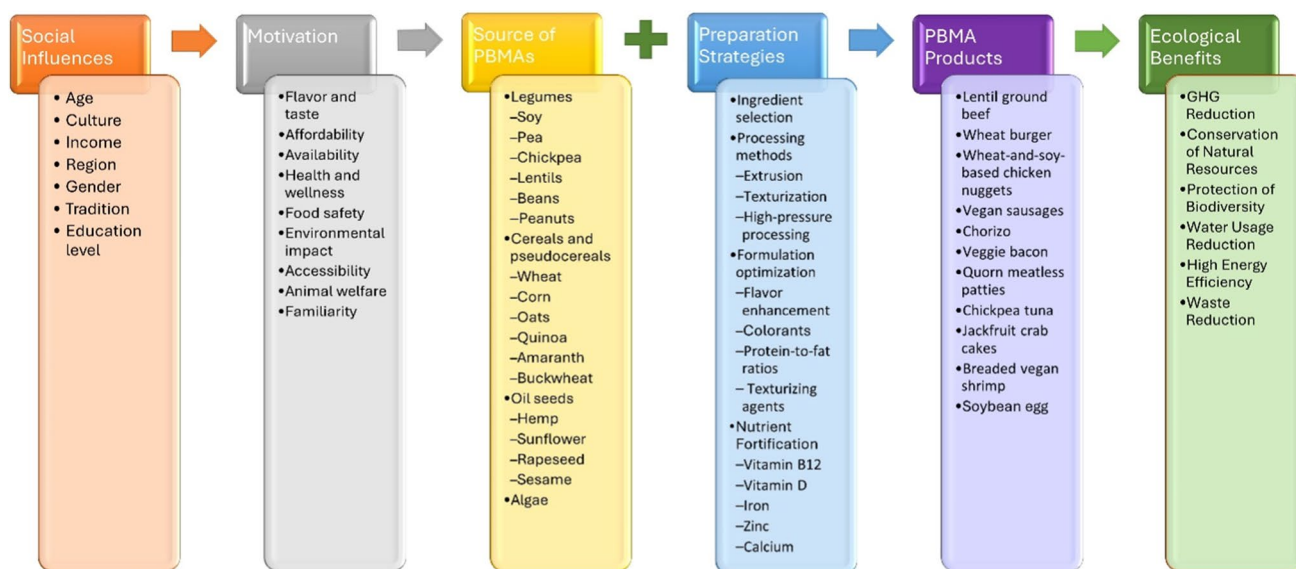


Fig. 2 An overview of plant-based meat analogs (PBMA) development. GHG: Greenhouse gas emissions

limitations. In addition to accommodating people with lactose intolerance, egg, and seafood allergies, or other food sensitivities, they also present solutions for vegetarians, vegans, or flexitarians [120].

As the trend toward a plant-forward diet gains popularity and becomes more socially acceptable, people could be more receptive to exploring PBMA. Customers gravitate toward plant-based foods out of concern for the effects of animal agriculture on the environmental impact, including greenhouse gas emissions, land use, waste production, water consumption, and deforestation (Fig. 2). Eco-aware customers might discover PBMA more sustainable because they usually result in less of an impact on the environment than conventional meat products [121, 122]. Ethical concerns and the desire to alleviate animal suffering influence the actions of many customers. Customers may contribute to a more compassionate and ethical food system that decreases or removes the need for animal exploitation and slaughter by choosing PBMA [115, 123].

The PBMA are used in various culinary applications, including ground beef, burgers, sausages, meatballs, and seafood products [124]. Their versatility allows for integration into a wide range of traditional meat-based recipes, thereby expanding their marketability. The commercial sector for PBMA has experienced significant growth, driven by increasing consumer awareness of health, environmental, and ethical issues. Major food companies and startups alike are investing in research and development to improve the taste and variety of plant-based products [113, 125, 126].

The challenges in the development of plant-based meats include achieving a convincing texture, addressing sensory aspects like juiciness, and achieving cost competitiveness.

Overcoming these challenges is crucial for broader consumer acceptance. The major challenge is in imitating the taste, texture, and mouthfeel found in conventional meat products. Despite developments in plant-based innovations, some customers might discover that PBMA don't taste and feel fairly like the conventional meats they are used to. Also, regulatory frameworks and labeling standards are evolving to accommodate plant-based meats. The use of terms like "burger" and "sausage" on packaging is a subject of regulatory discussions in some regions of the world. The food safety concerns of the chemicals, preservatives, and genetically modified organisms present in PBMA may exist among certain customers. Confidence among consumers may be increased by addressing these concerns and maintaining transparent information regarding ingredients and origin [127–129].

Plant-based foods may still be stigmatized and discriminated against by specific customers who think they are less enjoyable or of lower quality than meat-based foods. Besides, there could be misunderstandings regarding the nutritional content of plant-based meat substitutes regardless of their positive health effects. Confusion and skepticism may result from some customers' false belief that all plant-based products are inherently healthier than animal products.

In certain geographic regions or marketplaces, PBMA might not be as extensively accessible or available compared to conventional meat products. Customers may find it challenging to discover plant-based alternatives due to limited availability, especially in a region lacking nutrition specialists or health food stores. The developing regions of the world are most prone to this situation.

Furthermore, since PBMAAs could be more expensive or comparable to conventional meats, people on low incomes may find it more challenging to purchase them [154]. Some are quite cheaper [155] but the possibility of accessing them remains low. High or comparable costs may be an obstacle to acceptance, particularly for cost-conscious or low-income customers [155].

Although PBMAAs have many advantages for the environment and human health, their higher price tag than traditional meats may prevent them from being widely adopted, particularly by people who are budget-sensitive or have low incomes. The pricing disparity between PBMAAs and traditional meats is seen in the accompanying table and study, which also highlights the financial difficulties that customers confront. A comparison of the costs of PBMAAs, beef, and chicken is shown in Table 6. PBMAAs are significantly higher in costs. For instance, the well-known PBMAAs “Beyond Burger” and “Impossible Burger” are far more expensive than regular ground beef and poultry. Specifically, the “Impossible Burger” costs around \$6.80 per pound, whereas the “Beyond Burger” costs about \$6.25. In contrast, the price per pound for ground beef and chicken breast is \$4.49 and \$3.27, respectively. For other PBMAAs, at an average price of \$5.50 to \$5.99 per pound, items like “MorningStar Farms Grillers” and “Gardein Beefless Ground” exhibit a higher price point.

The purchase of PBMAAs might be difficult for low-income households because of food budget restrictions. When considering the total amount of protein ingested over time, the \$1 to \$3 price difference per pound might add up. One factor contributing to the cost problem is the restricted availability of PBMAAs in low-income areas. Standard meats are more accessible and frequently offered at reduced costs when purchased in large quantities [156]. For consumer acceptance and market growth, exorbitant costs put off cost-conscious customers who value affordability over the advantages of PBMAAs for the environment or their health. This category includes families with limited food budgets in

addition to low-income households. PBMAAs have the ability to save costs as they expand manufacturing and enhance supply networks. Nevertheless, economic constraints will still affect consumer acceptability until considerable price parity with conventional meats is reached [157].

USDA Economic Research Service: Provides data on average retail prices for meat products in the United States. <https://www.ers.usda.gov/>

Beyond Meat Official Website: Pricing information for Beyond Burger. <https://www.beyondmeat.com/en-US/>

Impossible Foods Official Website: Pricing information for Impossible Burger. <https://impossiblefoods.com/>

Gardein Official Website: Pricing information for Gardein Beefless Ground. <https://www.gardein.com/>

MorningStar Farms Official Website: Pricing information for MorningStar Farms Grillers. https://www.morningstarfarms.com/en_US/home.html

Quorn Official Website: Pricing information for Quorn Meatless Grounds. <https://www.quorn.us/>

Moreover, consumer acceptability of PBMAAs can be influenced by dietary choices and cultural background. Certain cultures place a strong emphasis on meat in traditional cuisine, which makes it difficult for customers to switch to plant-based alternatives without compromising the authenticity of their culture. Consumers who are unfamiliar with plant-based food preparation and recipes may find it difficult to adapt to them. Therefore, instruction and support are necessary to help them make the transition to a plant-based diet [130, 131].

Conclusions and Prospectives

PBMAAs represent a dynamic and rapidly evolving sector of the food industry. While they offer promising alternatives to conventional meat, ongoing research and development are essential to further improve taste, texture, and nutritional profiles, making them more widely accepted by consumers. Additionally, addressing sustainability concerns and providing clear labeling will play a role in shaping the future of plant-based meats in the global food market. PBMAAs typically have a lower environmental impact than traditional meat in terms of land use, water consumption, and greenhouse gas emissions.

Extrusion has become the most favorable means of processing meat analogs and the high temperatures used for extrusion destroy the often-expensive aromas or heat-sensitive plant-based colorants. Therefore, such issues can be avoided by adding the ingredients post-processing. This calls for innovative thermal-friendly processing techniques. More studies are warranted to scope and underscore the

Table 6 Cost comparison in 2024 between PBMA products, beef and chicken

Product	Average Price per Pound (USD)	Reference
Ground Beef (80% lean)	\$4.49	[1]
Chicken Breast	\$3.27	[1]
Beyond Burger	\$6.25	[2]
Impossible Burger	\$6.80	[3]
Gardein Beefless Ground	\$5.99	[4]
MorningStar Farms Grillers	\$5.50	[5]
Quorn Meatless Grounds	\$5.99	[6]

Sources:

significance of the analogs and comprehend their texture or structure–function relationships. More attention and critical analysis of studies promoting low protein content and quality in commercial meat alternatives are necessary. These studies, for instance, blend different protein sources to deliver a complete amino acids profile. The digestibility of these alternatives must also be ascertained. Above all, robust studies of the safety, allergenicity, and toxicity of the PBMA must be continuously researched, especially on a human intervention basis.

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- McClements, D. J. (2023). Soft Matter Physics Approaches for Creating Plant-based Meat Analogs. *Current Opinion in Food Science*, 101,120.

This article highlights computational approaches to the properties of polymer and particle gels assembled from plant proteins, polysaccharides, and lipid droplets.

- Joshi, K., Shabani, E., Kabir, S. F., Zhou, H., McClements, D. J., & Park, J. H. (2023). Optimizing Protein Fiber Spinning to Develop Plant-Based Meat Analogs via Rheological and Physicochemical Analyses. *Foods*, 12(17), 3161.

This study demonstrated that fiber-spinning technology can produce fibrous ingredients for PBMA. The article also explains the operating and formulation conditions that could be optimized to improve the physicochemical and functional properties of the fibrous components.

- Aksoylu Özbek, Z., Taşkın, B., & Sözeri Atik, D. (2023). Fortification of Plant-Based Food Analogs. In *Plant-Based Foods: Ingredients, Technology and Health Aspects* (pp. 35–72). Cham: Springer International Publishing.

The chapter explains the fortification of PBMA through direct inclusion, bio-enrichment by fermentation, or incorporation of various target compounds or fruits. It also discussed the pros and cons of PBMA and popular fortification strategies of plant-based foods.

- Wang, Y., Lyu, B., Fu, H., Li, J., Ji, L., Gong, H., ... & Yu, H. (2023). The development process of plant-based meat alternatives: Raw material formulations and processing strategies. *Food Research International*, 112,689.

The authors described the current composition of raw materials used in the production of PBMA. They also explained the interactions between protein molecules and the effects of protein aggregation and

phase separation on fiber structure formation in PBMA.

Competing Interests

The authors declare no competing interests.

Ethics Approval

No ethical approval was needed for this study.

Acknowledgements No external funding is received for this work.

Authors' Contributions Original draft – ZY, CL, XZ, CW, OJO, CCL, TJA. Revision – ZY, CCL, TJA. Conceptualization, and final manuscript – TJA.

Data Availability There are no new datasets generated in this manuscript.

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