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Review Article

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In-depth Analysis of Proteins, Binders, Fats and Flavoring Agents in Plant-based Meat Formulation: A Comprehensive Review

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Abstract

This review paper examines the critical roles played by proteins, binders, fats, and flavoring agents in enhancing the texture, sensory attributes, nutritional profile, and stability of plant-based meat alternatives (PBMAs). It analyses key ingredients such as soy, pea, and wheat gluten proteins; hydrocolloids and dietary fibers acting as binders, structured vegetable oils and oleo gels, and specific aroma compounds. This review focuses on the functional contributions of these ingredients in mimicking the fibrous structure, juiciness, and umami flavor of animal meat. Amid growing consumer demand driven by environmental, ethical, and health concerns, this analysis highlights recent advancements in processing, such as high-moisture extrusion and emulsion gels that enhance product quality and market acceptability. Alongside a discussion of challenges such as cost constraints, flavor deficiencies, and nutritional shortcomings, this article also explores future trends, including precision fermentation and clean-label formulations. These advancements aim to narrow the gap between the sensory attributes of plant-based meat products and conventional meat, thereby fostering their widespread acceptance.

Keywords

Plant-based meat, Plant proteins, Hydrocolloids, Flavoring agents, High moisture extrusion

Introduction

Rising awareness of the negative effects of traditional meat production on the environment, ethics, and human health has led to a significant shift in the global food market. To tackle these challenges, PBMAs have emerged as a viable option, utilizing plant-based ingredients to mimic the nutritional value and flavor of conventional animal meat. Without compromising the taste, composition, or nutritional flexibility, these products aim to offer consumers a more ethical and sustainable food choice [1].

Meat substitutes that emerging from plants provide a sustainable protein source that aims to mimic the taste, texture, color, and nutritional aspects of specific meat products. Typical PBMAs, also referred to as mock meat, have been essential in Asian vegetarian cooking [2]. The meat analogue is a food that mirrors meat in the structure but varies in composition [3]. A variety of factors influence where the sources derive from, alternative meats fall into four main categories: plant, microorganism, animal, and insect-based meat substitutes [4]. Muscle fibers (myofibrillar proteins), connective tissue (collagen), fat, and water make up most of the red meat [5].

The systematic arrangement of muscle fibers and the existence of connective tissues contrast to create a unique fibrous texture, which enhances tenderness.

Throughout the cooking process, the fat percentage incorporates taste, hydration level, and marbling. The heat treatment aids in the effective interaction of the elements to modify the texture, release flavor compounds, and enhance the cooked meat's color and aroma [6].

Recent advancements in food processing, protein structuring, and flavor development have contributed to the rapid evolution of the plant-based meat sector Onwezen et al. [7].

Companies, for example Beyond Meat and Impossible Foods have played a vital role in shaping consumer perception and market demand, which has helped plant-based meat products achieve acceptance. With the objective of significantly enhancing product quality and customer acceptance, academic research and innovation are still investigating new plant protein sources, functional additives, and production processes.

The present status of plant-based meat is thoroughly examined in this review study. It explores critical topics such as ingredient composition, manufacturing processes, dietary concerns, customer attitudes, market dynamics, and environmental impacts. This study attempts to provide a critical viewpoint on the potential of plant-based meat to support more ethical, health-conscious, and ecological food systems by combining data from industry advancements and scientific research.

The objective of creating PBMAs is to precisely replicate the structural, functional, and sensory qualities of animal-derived meat. Designing plant-based substitutes that deliver an identical experience in terms of taste, texture, juiciness, and appearance requires an understanding of the structure and behavior of animal-derived meat throughout processing and cooking [5].

Key Components and Their Functional Roles

Texture, juiciness, flavor, and overall appearance are essential features that PBMAs must replicate to successfully resemble the sensory experience of meat obtained from animals [8]. To achieve the desired texture and mouthfeel, the fibrous, elastic structure found in muscle tissue must be replicated, and juiciness depends on retaining moisture and fat [9]. The complex umami and roasted overtones characteristic of cooked meat are produced by flavor development, especially through Maillard reactions and lipid oxidation [10]. Consumer acceptability and perception are also greatly influenced by visual signals, such as the red color of fresh meat and surface browning during cooking. Plant proteins, structured lipids, binding agents, flavor precursors, and natural colorants must be carefully combined in a formulation that closely resembles the physicochemical behavior of meat during preparation and consumption to achieve these functional aims [11].

Protein Sources for Plant-based Meats

Soy protein

Soy proteins are widely utilized in the food industry to create a variety of nutritious meals as they include amino acids that are essential for human health across all age groups. In formulations used to develop meat substitutes, soy proteins are utilized in the form of flour, soy isolates, or soy protein concentrate [12]. Because soy proteins offer the required functional qualities of water-holding, gelling, fat-absorbing, and emulsifying, they have been used extensively as meat substitutes. The least processed ingredient in soybean products is soy flour. The market provides a variety of flour, including defatted, full-fat, and toasted flour (Figure 1) [13].

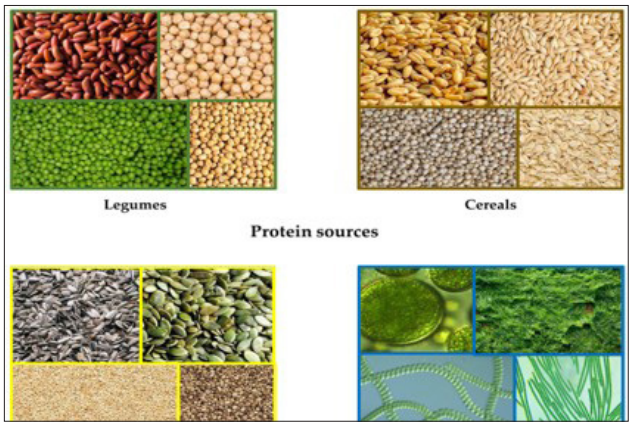

Figure 1: Types of protein sources used in developing plant-based meat [14].

Pea protein

From a nutritional perspective, green peas (*Pisum sativum*) are a variety of pulses that provide a significant amount of protein. Green peas offer high-quality protein, dietary fiber, starch, carbohydrates, and various kinds of vitamins and minerals, which serve as necessary sources of nutrients for a balanced diet. In terms of consumption, green peas are often available on store shelves as canned and frozen foods or as a pea protein in PBMAs, including veggie meatballs, sausages, patties, and hamburgers [15].

Wheat gluten and other cereal proteins

80 - 85% of the protein in wheat flour is gluten. It is composed of polymeric glutenin proteins with molecular weights ranging from 80,000 to several million and monomeric gliadin with molecular weight between 30,000 and 60,000 [16].

Novel and emerging protein sources

Mycoprotein is a high-protein substance derived from fungal mycelium [17]. Since entering the market about 40 years ago, mycoprotein-based meat substitutes have grown to be a natural, safe, and generally accepted plant-based option for individuals who wish to reduce the consumption or eliminate meat consumption. Mycoprotein innovation has seen a significant comeback in recent years, with several new businesses creating innovative mycoprotein products and utilizing a greater variety of fungal species and growing techniques. But there are also concerns concerning mycoprotein's effectiveness as a new food ingredient in terms of its production robustness and sustainability, as well as its potential for future international market expansion (Table 1) [18].

Table 1: Comparison of alternate protein sources used in plant-based meat [19].

Protein source	Protein content (%)	Key functions	Advantages	Limitations
Soy protein (isolate/concentrate/flour)	65 approx.	Water-holding, gelling, emulsifying, fat-binding	High functionality, versatile processing	Potential allergen, beany flavor
Pea protein	40 approx.	Nutrition, fiber addition	High protein quality, low allergen potential	Low solubility, green off flavors
Wheat gluten	46 - 50 approx.	Fibrous structure through disulfide bonds	Excellent texture imitation	Not suitable for individuals with celiac disease
Mycoprotein	45 approx.	Natural texture, sustainability	Long market presence, scalability	Production sustainability concerns

Binders and Texturizing Agents

Hydrocolloids are water-soluble biopolymers composed of high molecular weight polysaccharides that are utilized as gelification agents, viscosity builders, and food system stabilizers. Gum arabic (acacia), tragacanth, xanthan, and certain modified gums are some of the hydrocolloids that have been identified as food additives with unique properties such as "prevention of precipitation of suspended solid particles and formation of oil droplets." It is still not clear how these gums work as emulsifiers [20]. The fibrous structure of PBMAs is an essential component in their texture and sensory value. The primary ingredient of plant-based meat substitute is wheat gluten, usually obtained from different protein sources, for example soy or pea, which forms an interconnected network through intramolecular and intermolecular disulfide bonds to give the product a fibrous structure. Furthermore, wheat gluten can improve the end product's texture, binding qualities, moisture retention, and sensory qualities when added to PBMAs. However, PBMAs that contain gluten are unsuitable to people with celiac disease [21]. Hydrocolloids are promising substitutes for wheat gluten, given their ability to mimic its functionality and texture. To enhance the functionality of certain hydrocolloids, such as high acyl gellan gum, low acyl gellan gum, high methoxylated pectin, low methoxylated pectin, and xanthan, appropriate salt concentrations are required to produce a network, which can lead to the formation of a fibrous structure in PBMAs [22]. Salts, such as sodium chloride and calcium chloride, are often used to improve the sensorial properties of PBMAs, such as their taste and texture. Moreover, calcium chloride serves as a vital calcium fortifier in food products, influencing hydrophobic interactions and cross link density as an excellent cross-linking agent [21].

Starches and Flours

Over the past few decades, a lot of study has been done on the use of starch in meat products. In processed meat, such as sausages or beef patties, it serves as a filler. These plant-based fillers aid in binding water and are often efficient bulking agents. Added to the product to bind water that would otherwise be emitted, starch is regarded as an effective bulking agent. Its capacity to absorb water can be further enhanced by adding pre-gelatinized starch. When starch is pre-gelatinized, it binds water at a lower temperature, which is advantageous since it stops the meat from losing water when heated. The ability of starch to bind water makes it possible to further lower the calorie content of foods like sausages. By modifying the lipid profiles to incorporate larger levels of unsaturated fats, starch can help the products to maintain their sensory and textural qualities. For instance, it can make products firmer and stronger when animal fats are replaced with vegetable oils. Additionally, the incorporation of starch in meat emulsions has been shown to produce a stronger and more compact heat-activated protein network. According to reports, using starch in meat products has the benefits of being inexpensive and providing good control over functional characteristics such as water solubility, cold swelling capacity, and rheological qualities through chemical or physical alteration [23].

Fiber-based Binders

Since the characteristics of dietary fibers vary widely, the final texture of the product will be influenced by the formulation selected. Dietary fibers have been shown to affect food product sensory qualities (flavor, texture, and color), increase viscosity, create gels, and influence hydration. Particle size, shape, arrangement, porosity, and dietary fiber solubility all affect those functional characteristics. Fruit and vegetable-based dietary fibers, for instance, include a comparatively high percentage of soluble dietary fiber, which confers upon them greater hydration, gelling, oil-holding capacity, and water-holding capacity. The hydrophilic character of dietary fiber is associated with water holding capacity. In the three-dimensional network of polysaccharide molecules connected to water molecules via hydrogen bonds, soluble dietary fiber captures water. Their large surface area and porosity, which bind dietary fibers to lipids, are responsible for their oil-holding capabilities. Individual ingredients like pectin, glucomannan, carrageenan, alginate, inulin, resistant starch, fructooligosaccharides, polydextrose, carboxymethyl cellulose, hemicellulose, and lignin, as well as components like bran, pomace, peel, and vegetable by-products, are examples of dietary fiber sources that are frequently found in food (Table 2) [24].

Fat Sources and Structuring Techniques

Plant-based oils (e.g., coconut, sunflower, and canola)

In terms of softness, juiciness, and general palatability, canola oil exhibits outstanding characteristics as a fat alternative. Furthermore, sunflower oil improves nutritional qualities and encourages the synthesis of phenolic compounds. Olive oil, rich in oleic acid and other unsaturated fatty acids, has been

Table 2: Classification of binder types, their functional roles, and effects on texture of plant-based meat [25].

Binder type	Examples	Key roles	Impact on texture
Hydrocolloids	Agar, alginic acid, carrageenan, sodium alginate, gellan gum, guar gum, gum tragacanth, gum arabic, glucomannan, karaya gum, locust bean gum, tara gum, and xanthan gum	Thickeners, gel-forming agents, emulsifying agents, stabilizing agents, fat substitutes, clarifying agents, coagulating agents, clouding agents	Fibrous network formation, moisture retention
Starches/flours	Pre-gelatinized starch	Water-binding, bulking, calorie reduction	Firmer emulsions, heat stability
Fiber-based	Inulin, bran, pomace	Hydration, oil-holding, viscosity	Soluble fiber enhances gelling, insoluble add bulk

associated with a reduced risk of cardiovascular diseases. Other vegetable oils have been used in meat alternatives, including margarine, shortening, orange oil, palm oil, and castor oil. Regardless of the amount of oil applied, PBMAs containing orange oil exhibited significant 2,2-diphenyl-1-picrylhydrazyl radical scavenging activity, a high moisture content, and a relatively high liquid retention capacity. Additionally, sensory evaluation shows the juiciness of soybeans enhanced while the odor reduced. By improving meat juiciness and lowering the product's soybean odor, orange oil enhanced the quality and appeal of meat substitutes. Additionally, low-fat chicken sausages were made using garlic inulin as a fat alternative. Canola oil is used as a solid fat substitute in plant-based cheese, cold-pressed pumpkin seed oil is used to make Bologna-style sausages instead of beef fat, and carrots and lemon are used as fat substitutes to improve the physicochemical, textural, and sensory aspects of low-fat beef burgers. These applications additionally include fibers.

Structuring fats: Oleo gels and emulsions

Oleo gel systems have become popular replacements for traditional fats that include large quantities of saturated and trans fats. Lipids made of unsaturated triacylglycerols, such liquid vegetable oils or semisolids, have a gel-like form in oleo gel systems. As a result, oleo gels are made up of a liquid organic phase that is controlled using gelling agents to create a three-dimensional network that traps oil. Despite containing a high proportion of unsaturated fatty acids, these oleo gels are heat-reversible and act similarly to solid fats. Importantly, triacylglycerol molecules do not need to undergo any structural or chemical alterations to create an oleo gel, preserving the oil's original molecular distribution, unsaturated fatty acid content, and nutritional qualities. To create oleogels, gelators (such as waxes, fatty acids, fatty alcohols, monoacylglycerols, and phytosterols) are typically dissolved in vegetable oil at low concentrations, heated (above the melting point), and then cooled to gel. One emerging approach is the use of oleo gels as substitutes for solid fats in water-in-oil emulsions. The physical and structural properties of oleo gels, which may be made from a variety of vegetable oils, are closely linked to the properties of the lipid phase. Given its composition, availability, and affordability, soybean oil, high-oleic sunflower oil, olive oil, and palm oil have the potential to be used in the development of oleo gels [26]. Emulsion gels, which are produced by dispersing an emulsion into a gel system, in which the gel acts as the continuous phase and the emulsion as the dispersed phase, possess a stronger structure and a greater ability to hold water than emulsions or gels alone. Exploring the many uses of emulsion gels in food compositions has received a lot of interest. They may be used to make low-fat foods, replace or partially reduce the amount of sugar and salt in foods, and improve the viability of probiotics in the digestive system (Table 3) [27].

Flavoring Agents and Aroma Compounds

Natural and synthetic flavoring

PBMAs are generally designed to resemble the flavor of processed meat products, although meat itself has a very neutral flavor. Therefore, depending on whether the final product represents marinated meat, burgers, or sausages, in addition to rectifying the off flavors, the required scent and taste must be added. When testing commercial meat imitation burger items, researchers looked at how cooking affected the creation of aromas and discovered that the flavoring components employed mostly impact the fatty acid composition and volatile flavors compound profile. Therefore, choosing the appropriate spices can improve the items' acceptability among consumers [28].

Conclusion

Overall, the development of plant-based meat formulation is at a turning point that will be influenced by both opportunities and challenges. On the one hand, constant innovation in taste, texture, and nutrition, driven by developments in precision fermentation, new protein sources like legumes, fungi, and algae, as well as hybrid formulation. Promises to close the sensory experience and consumer appeal

Table 3: Fat types, nutritional benefits, and structuring method used in plant-based meat [26].

Fat type	Examples	Nutritional benefits	Structuring method
Plant oils	Canola, sunflower, olive, and coconut	Unsaturated fats, antioxidants	Emulsions for juiciness
Oleo gels	Soyabean oil with waxes/phytosterols	Heat-reversible solid like fats, no chemical change	Traps oil in three-dimension networks
Emulsion gels	Oil-in-gel dispersions	Higher water-holding than gels	Low-fat spreads, probiotics viability

gap between plant-based products and traditional meat. Health and sustainability remain strong incentives, driving businesses to decrease processing, purify ingredient lists, and give ethical and environmental practices priority. However, significant obstacles still exist. Cost is still a significant barrier; many PBMAs will not be able to compete on price with their traditional equivalents unless production is scaled up and supply networks are optimized. Consumer skepticism continues to compromise confidence and acceptance, particularly regarding "ultra processed" labelling, nutritional completeness, and naturalness. To maintain expansion, it is also essential to handle regulatory frameworks, ingredient procurement, and increasing production infrastructure. Future developments in plant-based meat formulations are expected to focus on several key trends. Fermentation-derived ingredients and novel ingredient combinations will be used to enhance nutritional value, taste, and texture. At the same time, manufacturers are likely to prioritize minimal processing and clean-label products to address consumer concerns about health, trust and transparency. Continued technological innovation, economics of scale, and local sourcing strategies are expected to reduce production costs and improve affordability. Additionally, as demand grows in regions such as Asia, Latin America, and the Middle East, companies will increasingly customize formulations to match local taste preferences, ingredient availability, and regulatory requirements. Furthermore, even though PBMAs might not ever be able to fully capture every aspect of meat obtained from animals, their development is probably going to establish a solid and long-lasting place in the world's protein market. Plant-based meat has the potential to not only to replace traditional meat but also to completely change diets throughout the world, with positive direct benefits for the environment, animal welfare, and human health if the sector keeps focusing on innovation, transparency, and affordability.

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None.

Conflict of Interest

None.

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