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A Narrative Review of the Sensory and Nutritional Challenges in the Development of Plant-based Meat Analogues

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Abstract

The global shift towards sustainable and ethical diets has accelerated the demand for plant-based meat analogues, yet their widespread adoption is hindered by significant challenges in replicating the complex sensory attributes and nutritional profile of animal meat. This review overviews current research to delineate these hurdles and the innovative strategies being employed to overcome them. A critical examination of the existing literature is necessary to consolidate knowledge and guide future advancements in this rapidly evolving field. This review meticulously examines the primary obstacle of mimicking meat's anisotropic, fibrous structure, detailing the role of ingredient functionality and processing technologies like high-moisture extrusion and shear cell technology. It further explores the complexities of flavor profiling, including the origins of undesirable off-flavors and mitigation strategies through fermentation and enzymatic treatments. The pursuit of nutritional equivalence is analyzed, focusing on protein quality, micronutrient fortification, and the incorporation of functional ingredients such as algae and grape pomace. Advanced evaluation methods for ensuring product quality and safety are also discussed. Central to the review is an in-depth analysis of how these technical factors collectively influence consumer acceptance, which is ultimately dictated by the product's sensory experience. Finally, key clinical studies comparing the physicochemical and sensory properties of plant-based analogues to conventional meat are highlighted to provide empirical context. Future research must focus on integrating multidisciplinary approaches that combine biotechnology with material science to create next-generation analogues with superior meat-like fidelity. Exploring underutilized protein sources and optimizing scalable, cost-effective processing techniques will be crucial for enhancing sustainability and market accessibility. Ultimately, closing the remaining gaps in sensory satisfaction and nutritional completeness is imperative for plant-based meat analogues to fulfill their potential as mainstream staples in sustainable food systems.

Keywords: Consumer acceptance, Flavor profiling, Nutritional equivalence, Plant-based meat analogues, Processing technologies, Sensory attributes, Sustainable food systems, Texture

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Introduction

The development of plant-based meat analogues has garnered significant attention due to increasing consumer demand for sustainable, ethical, and health-conscious food options [1-7]. Central to this development are the sensory and nutritional challenges that must be addressed to produce products that closely mimic traditional meat in both appearance and health benefits. The literature highlights a multifaceted approach involving ingredient functionality, processing technologies, and consumer acceptance to overcome these challenges. One of the primary hurdles in creating convincing plant-based meat analogues is replicating the sensory attributes of animal meat, including texture, flavor, appearance, and mouthfeel [8-13]. Singh et al. [14] emphasize that recent advancements focus on utilizing vegetal proteins to develop novel foods that can emulate these sensory qualities. Similarly, Zhang et al. [15] discussed the importance of consumer acceptance, which hinges on the product's ability to meet sensory expectations. The challenge lies in achieving a fibrous, meat-like texture, which is often difficult due to the inherent properties of plant proteins (Table 1).

The functionality of ingredients plays a crucial role in addressing these sensory challenges. Kyriakopoulou et al. [16] highlights that key ingredients such as proteins, fibers, and additives are essential for recreating the physical sensations associated with meat. They underline the importance of ingredient functionality, particularly in forming fibrous structures that resemble muscle tissues. Wang et al. [17] further elaborate on the importance of raw material formulation and processing strategies aimed at improving fiber structure formation, which is vital for mimicking the texture of meat. Processing technologies are equally critical in overcoming sensory limitations. Su et al. [18] review the technological challenges faced from the perspective of plant proteins, emphasizing the need for innovative processing methods to shape myofibril-like fibrous structures. Techniques such as extrusion, fermentation, and novel biotechnological approaches are being

Table 1: Common plant protein sources in meat analogues: Functionality, limitations, and applications.

Protein source	Key functional properties	Advantages	Key limitations/challenges	Common applications in meat analogues
Soy protein (isolate/concentrate)	High gelation, water/fat binding, emulsification	Neutral flavor, complete protein profile, widely available, well-studied	Off-flavors (beany, grassy), allergen concerns, genetic modification perceptions	Burgers, grounds, sausages, chicken nuggets (as the primary protein base)
Pea protein (isolate/concentrate)	Good gelation, emulsification, and foaming capacity	Hypoallergenic, non-genetically modified organism, clean-label appeal, sustainable cultivation	Gritty mouthfeel, strong beany/earthy off-flavors, limited solubility	Burgers, grounds, sausages (often blended with other proteins to mask flavor)
Wheat gluten	Excellent viscoelasticity, cohesiveness, and film-forming ability	Forms strong, fibrous, chewy structures essential for texture	Major allergen (celiac disease), can create a dense, rubbery texture if over-used	Whole-muscle analogues (strips, chunks), used as a binder to enhance chewiness
Mycoprotein	Inherently fibrous, high water-binding capacity	Meat-like texture, high in dietary fiber, unique umami flavor	Requires specific fermentation process, potential for consumer skepticism (origin)	Chicken-style pieces, fillets, grounds
Faba bean protein	Good solubility, gelation, and foaming	Sustainable (nitrogen-fixing crop), emerging source with potential	Pronounced beany flavor, dark color, can have antinutritional factors	Emerging use in burgers and blends, often fermented to reduce off-flavors
Potato protein	High thermal stability, good emulsification	Hypoallergenic, neutral color, non-genetically modified organism	Can have a bitter aftertaste, limited functionality in some systems	Used as a supplemental protein for emulsification in sausages and patties
Rice protein	Hypoallergenic, easily digestible	Mild, neutral flavor, well-tolerated	Low solubility, poor gelation, often gritty, incomplete amino acid profile (low lysine)	Often used in blends for its hypoallergenic property, not a primary structural protein
Lupin protein	High water and fat binding capacity	High protein content, favorable nutritional profile	Strong, bitter off-flavors, allergen concerns for some individuals	Limited but emerging use, often in fermented products or as a flour

explored to enhance textural properties. Milcarz and Harasym [19] discuss the promising role of solid-state fermentation in improving the quality of plant-derived proteins, which can contribute to better texture and flavor profiles. These biotechnological interventions aim to produce more realistic meat analogues by modifying protein structures and reducing undesirable flavors.

Flavor development remains a significant challenge, particularly in eliminating off-flavors such as the beany taste often associated with legume proteins. Zhang et al. [15] note that consumer acceptance is heavily influenced by flavor, which must be carefully managed through processing and ingredient selection. The use of biotechnological methods, such as fermentation, has shown potential in mitigating these flavors, as highlighted by Milcarz and Harasym [19], who suggest that fermentation can modify flavor compounds and improve overall palatability. Nutritional equivalence is another critical aspect of plant-based meat analogue development. Mishal et al. [20] focus on formulating meat analogues with similar nutritional profiles to animal meat, emphasizing the importance of balancing macronutrients and essential amino acids. Da Silva et al. [21] further explores the potential of plant proteins, fibers, and antioxidant compounds to enhance the nutritional value of meat analogues. They stress that achieving a nutritionally complete product requires careful selection and processing of ingredients to ensure adequate protein quality and micronutrient content.

The incorporation of functional ingredients such as algae and grape pomace has been explored to enhance both nutritional and functional properties. Matos et al. [22] and Kurćubić et al. [23] discuss the potential of algae and grape pomace, respectively, in enriching plant-based products with bioactive compounds, antioxidants, and dietary fibers. These ingredients not only improve nutritional profiles but also contribute to the functional and sensory attributes of meat analogues. Consumer acceptance remains a pivotal factor influencing the success of plant-based meat analogues. Szenderák et al. [24] review consumer perceptions, noting that sensory attributes are among the most significant determinants of acceptance. Hassoun et al. [25] highlight that plant-based foods constitute the largest segment of alternative proteins, yet consumer preferences are shaped by sensory experiences, safety, and perceived health benefits. Therefore, technological innovations aimed at improving sensory qualities are essential for broader market adoption.

Advancements in evaluation methods are also crucial for ensuring product quality. Alam et al. [26] review cutting-edge technologies for assessing food safety, nutritional value, and sensory attributes, which are vital for refining plant-based meat analogue formulations. These evaluation techniques help identify areas needing improvement, ensuring that products meet consumer expectations and safety standards.

In summary, the development of plant-based meat analogues involves overcoming significant sensory and nutritional challenges. Achieving realistic texture and flavor requires sophisticated ingredient functionality and innovative processing technologies such as extrusion and fermentation. Nutritional adequacy demands careful formulation to match the macro- and micronutrient profiles of animal meat, often supplemented with functional ingredients like algae and grape pomace. Consumer acceptance hinges on the product's sensory appeal, safety, and perceived health benefits, which are being addressed through technological advancements and comprehensive evaluation methods. As research progresses, integrating biotechnological approaches and functional ingredients will likely play a pivotal role in creating plant-based meat analogues that are both appealing and nutritionally complete, paving the way for sustainable and health-conscious food systems.

The Texture Challenge: Mimicking Meat's Fibrous Structure

The challenge of mimicking meat's fibrous structure in plant-based meat analogues is a complex task that involves understanding and replicating the intricate texture of animal meat [27-35]. This involves not only the visible fibrous structure but also the underlying mechanical and sensory properties that contribute to the overall eating experience.

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The fibrous texture of meat is primarily due to its muscle fibers and connective tissues, which are difficult to replicate using plant-based ingredients. However, advancements in processing technologies (Table 2) and ingredient selection are paving the way for more realistic meat analogues.

Structural challenges and techniques

- Macro and meso scale structures: Traditional meat exhibits a fibrous structure at both macro (1 mm) and meso (50 to 200 µm) scales, which is not yet fully replicated in plant-based analogues. The latter often displays a porous structure without a clear fiber direction from the meso scale onward, which affects their texture properties [35].

- High moisture extrusion and shear cell technology: These are key processes used to create anisotropic structures that mimic muscle fibers. High moisture extrusion involves blending proteins with water and other ingredients, followed by controlled heating and cooling to achieve a fibrous texture. Shear cell technology deforms biopolymer blends at elevated temperatures, allowing the formation of fibrous structures upon cooling [36, 37].

- Ingredient selection: The use of proteins such as soy, wheat, and pea is common, but there is a growing interest in less refined ingredients like faba beans to enhance sustainability. Gluten plays a crucial role in forming fibrous structures, while other proteins act as fillers [36].

- Plant-based tissue engineering is a novel approach that deconstructs meat into its fundamental components and reconstructs them using plant-based ingredients. This method aims to replicate the complex structure and sensory experience of whole-muscle cuts of meat [27].

Processing and ingredient innovations

- Wet-spun fibroin fibers: Incorporating wet-spun fibroin protein fibers has shown promise in enhancing the textural properties of meat analogues, closely mimicking the texture of whole-muscle meat [38].

- Starch and water interaction: The interaction of starch and water in protein blends is critical for fiber formation. Modifying starch in situ and optimizing water distribution can significantly impact the textural properties of the final product [36].

- Technological challenges: Achieving the desired fibrous structure involves overcoming challenges related to ingredient functionality, processing conditions, and the balance between different phases in the blend [18].

Sensory and mechanical properties

- Texture profiling: Instrumental parameters such as Warner-Bratzler Shear force and tensile strength are used to evaluate the texture of plant-based analogues. These measurements correlate with sensory attributes like chewiness and mouthfeel, which are crucial for consumer acceptance [39].

- Anisotropy and mechanical properties: The degree of anisotropy, which refers to the directional dependence of mechanical properties, is a key factor in mimicking meat texture. Increasing protein content can enhance anisotropy, thereby improving the fibrous texture [37].

While significant progress has been made in mimicking the fibrous structure of meat, challenges remain in achieving the same level of texture and sensory attributes as animal meat. The development of plant-based meat analogues requires a multidisciplinary approach, combining insights from food science, material science, and sensory analysis. Future research should focus on optimizing processing techniques and exploring novel ingredients to further enhance the textural properties of meat analogues, making them more appealing to consumers seeking sustainable dietary options.

Processing Technologies for Structural and Sensory Enhancement

The development of plant-based meat analogues involves a variety of processing technologies aimed at enhancing both structural and sensory attributes to closely mimic traditional meat [40-45]. These technologies are crucial for improving the texture, flavor, and nutritional profile of plant-based products, making them more appealing to consumers. The primary focus is on achieving a meat-like texture and taste while maintaining nutritional value and sustainability.

Table 2: Key processing technologies for structural formation in meat analogues.

Processing technology	Principle	Impact on product structure	Key considerations	Product examples
High-moisture extrusion	Thermo-mechanical treatment in an extruder with >40% moisture; protein melt is aligned and texturized in a cooling die	Creates layered, anisotropic, fibrous structures closely resembling whole-muscle meat	High capital and energy cost; critical control of parameters (barrel temp, screw speed, cooling die design) is essential	Chicken breasts, beef steaks, pork chops, jerky
Shear cell technology	Application of simple shear stress to a protein gel at elevated temperature in a conical device	Forms anisotropic, fibrous structures; potentially more energy-efficient and gentler than extrusion	Currently limited scalability; more suitable for specific product types like chunks or strips rather than mince	Meat chunks for stews, pulled pork analogues, chicken strips
Electrospinning	Uses electric force to draw charged threads from a protein-polymer solution, creating ultra-fine fibers	Produces micro- to nano-scale fibrous scaffolds that can mimic muscle fibrils	Very low throughput, often requires food-grade solvents, not yet feasible for large-scale food production	Primarily research-stage; potential for premium structured products
3D printing (food additive manufacturing)	Layer-by-layer deposition of protein-based pastes or "inks" based on a digital model	Enables full customization of geometry, internal texture, and marbling with fat analogues	Limited by material printability (rheology) and production speed; currently used for high-value or customized products	Custom-shaped steaks, marbled cuts, complex geometric products
Wet spinning	Extrusion of a protein solution into a coagulation bath (acidic or saline), precipitating protein into filaments	Produces continuous, aligned protein filaments that can be bundled	Multi-step process, often involves and requires removal of chemical coagulants, lower efficiency	Research-stage and some early commercial products bundling filaments into muscle-like structures
Simple thermo-gelation	Heating protein slurry to denature and gel proteins, often combined with starch	Creates a homogeneous, isotropic gel structure with a crumbly or soft texture	Low cost, simple technology; does not create fibrous, anisotropic textures	Patties, sausages, meatballs (where a minced meat texture is acceptable)

Structural properties

- Extrusion technology: High-moisture extrusion is a widely used method for creating fibrous structures in plant-based meat analogues. It involves the use of high moisture content to facilitate the alignment of proteins, resulting in a meat-like texture. Key parameters such as barrel temperature, cooling die design, and moisture content are critical for optimizing the quality of the final product [41, 46]. Studies have shown that adding by-products like pineapple pomace can enhance the textural properties of extrudates, improving their resemblance to animal meat [47]. Micro-foaming is novel process that involves injecting nitrogen into the protein melt during extrusion, which can tailor the mechanical and textural properties of the product, enhancing consumer acceptance [48].

- 3D printing technology: Fibrous structure design, 3D printing offers precise control over the design of fibrous structures, allowing for the creation of complex textures that mimic muscle fibers. This technology can be combined with other methods like twin-screw extrusion to improve the structural fidelity of plant-based meat analogues. Despite its potential, 3D printing faces challenges such as optimizing the printing parameters and selecting suitable protein materials to achieve desired textural properties [49].

- Emerging non-thermal technologies: High pressure processing and pulsed electric field technologies modify protein structures under mild conditions, enhancing their functional properties without compromising nutritional quality. They are particularly useful for improving protein digestibility and bioavailability [50, 51]. Oxidation techniques like ultrasound, cold plasma, and ozone treatment can further modify protein structures, enhancing their textural and functional attributes [50].

- Ingredient and formulation considerations: Protein sources, the choice of plant proteins, such as soy, wheat gluten, and mycoproteins, play a crucial role in the textural and nutritional quality of meat analogues. Non-conventional sources like legumes and algae are also being explored for their superior properties [52]. Additives, ingredients like insoluble soy fiber and gellan gum can influence the formation of fibrous structures, although their interactions may sometimes hinder desired textural outcomes [53].

Sensory properties

- High-moisture extrusion: High-moisture extrusion is a prominent technology used to create a fibrous texture in plant proteins, closely resembling the structure of animal meat. This method involves the use of high moisture content during extrusion, which helps in aligning protein fibers to mimic meat texture [54, 55]. Despite its effectiveness, high-moisture extrusion requires sophisticated equipment and incurs high energy and maintenance costs, which can be a barrier to widespread adoption [54].

- Fermentation: Fermentation is employed to improve the sensory qualities of plant-based meat analogues, such as texture and flavor. Microorganisms like *Lactobacillus* and *Bacillus* species are used to enhance the fibrous structure and improve the chewiness and hardness of the products. This method also helps in reducing antinutritional factors and improving digestibility, although excessive fermentation can lead to undesirable textures [56].

- Protein extraction and modification: Advanced protein extraction methods, such as enzyme-assisted extraction and ultrasound-assisted extraction, are used to increase protein yield and improve the functional properties of plant proteins. These methods enhance protein solubility and foaming ability, which are crucial for texture and mouthfeel. Defatting raw pulse flour before protein extraction can further enhance protein content and quality, contributing to better sensory attributes [57].

- Flavor and nutritional enhancement: Incorporating ingredients like soy heme, mushroom extracts, and plant lipids can significantly enhance the flavor and juiciness of plant-based meat analogues, although these additions can increase production costs. Fortification with micronutrients such as iron and vitamin B12 is also essential to address nutritional deficiencies in plant proteins, but this can further elevate costs [54].

- Consumer perception and cooking methods: The sensory attributes of plant-based meat analogues are also influenced by consumer cooking methods. Techniques like baking and pan-frying can affect texture and flavor, with higher cooking temperatures enhancing sensory attributes through the Maillard reaction. Optimizing in-home cooking methods is crucial for improving consumer acceptance of plant-based meat analogues, as these methods can significantly alter the sensory experience [58].

While these technologies significantly enhance the structural and sensory qualities of plant-based meat analogues, challenges remain. The high cost of advanced processing techniques and ingredients can limit consumer accessibility. Additionally, achieving the perfect balance between texture, flavor, and nutritional value is complex and requires continuous innovation. Despite these challenges, the environmental benefits and growing consumer demand for sustainable food options drive ongoing research and development in this field.

Flavor Profiling and the Mitigation of Off-flavors

The flavor profiling and mitigation of off-flavors in plant-based meat analogues are critical for enhancing consumer acceptance and marketability [59-65]. Off-flavors, such as beany, grassy, and bitter notes, are common in plant-based proteins and can significantly deter consumer interest. Various strategies have been explored to address these challenges, focusing on understanding the formation mechanisms of these flavors and developing effective mitigation techniques. The following sections detail the key aspects of flavor profiling and mitigation strategies for plant-based meat analogues.

Flavor profiling

- Lipoxygenase pathway: The lipoxygenase-hydroperoxide lyase pathway is a major contributor to the formation of beany flavors in pea and soy proteins. This enzymatic process leads to the oxidation of polyunsaturated fatty acids, resulting in the production of volatile compounds such as aldehydes and alcohols, which are responsible for the characteristic off-flavors [66, 67]. In soy-based products, lipoxygenase oxidation-reduction reactions are particularly significant, contributing to the generation of undesirable flavors [67].

- Maillard reaction and lipid oxidation: The Maillard reaction, along with lipid oxidation, plays a crucial role in the development of off-flavors in plant-based foods. These reactions produce a variety of volatile compounds, including aldehydes, ketones, and pyrazines, which contribute to the complex flavor profile of plant-based meat analogues [59]. The interaction between these compounds and plant proteins can further exacerbate the off-flavor issue, as seen in soybean protein products [68].

- Fermentation and enzymatic treatments: Fermentation is a promising method for reducing off-flavors, as it can modify the aroma profile and decrease the concentration of undesirable compounds. The use of specific microbial strains during fermentation can enhance the sensory qualities of plant-based meat analogues [69]. Enzymatic treatments, such as the use of cyclodextrin glucanotransferase, have been shown to effectively mask off-flavors by reducing the volatilization of beany compounds. This method also improves the texture and water-holding capacity of the products [70].

- Physical and chemical processing: Physical processing techniques, such as extrusion, can influence the retention and release of off-flavors. Adjusting extrusion parameters can help control the formation of undesirable flavors during the processing of plant proteins [71]. Chemical methods, while effective, pose food safety concerns and may not be suitable for all applications. Therefore, a combination of enzymatic and non-thermal processing methods is often recommended [68].

- Genetic and agricultural factors: The generation of off-flavor compounds is also affected by genetic and environmental factors, such as species, cultivar, and farming practices. Advances in genome editing, like CRISPR-Cas9, offer potential for reducing off-flavors by altering the metabolic pathways involved in their formation [59].

Detection and analysis techniques

- Analytical methods: Techniques such as gas chromatography-olfactometry-mass spectrometry are used to identify and analyze volatile flavor compounds in plant-based meat analogues. These methods help in understanding the key flavor components and their impact on the overall sensory profile [72].

- Sensory evaluation combined with modern food flavor analysis techniques provides a comprehensive understanding of the flavor profiles and helps in identifying the specific off-flavors present in plant-based products [66].

- Advanced omics approaches, such as metabolomics, are used to analyze the interactions between flavor compounds and plant proteins, offering insights into the molecular basis of off-flavors [66].

Mitigation strategies

- Enzymatic treatments: Cyclodextrins produced by cyclodextrin glucanotransferase have been shown to effectively mask beany off-flavors in soy-based meat analogs. The cyclodextrin glucanotransferase-catalyzed reaction produces cyclodextrins that reduce the volatilization of off-flavor compounds, while also improving the texture and water- and oil-holding capacity of the patties. This method aligns with clean-label requirements as cyclodextrin glucanotransferase is inactivated after cooking, thus not considered an additive [70]. Enzyme restriction and β-cyclodextrin treatment, in conjunction with phospholipase A2, are highlighted as safe and effective techniques for reducing off-flavors in soy-based products [67].

- Microbial fermentation: Fermentation is a promising strategy for mitigating beany flavors, particularly in pea protein. It involves the use of specific microorganisms that can metabolize off-flavor compounds, thereby enhancing the aroma profile of the final product. This method is cost-effective and minimally impacts the protein matrix [66, 69]. Fermentation with microorganisms such as *Bacillus subtilis* and *Lactiplantibacillus plantarum* not only reduces off-flavors but also improves the nutritional and safety profile of plant-based meat analogs by enhancing digestibility and reducing allergenicity [56].

- Processing techniques: Adjusting extrusion parameters, such as temperature and pressure, can influence the interaction between plant proteins and flavor compounds, thereby controlling the retention and release of off-flavors. This approach is particularly relevant for soy protein during the extrusion process [71]. The use of antioxidant supplementation, pressure application, and controlled storage conditions are additional processing strategies that have been explored to mitigate off-flavors in plant-based foods [59].

- Sensory optimization: The sensomics concept involves identifying key taste and aroma compounds in meat products and incorporating these into plant-based alternatives to improve their sensory appeal. This approach requires precise selection and processing of plant proteins to achieve a flavor profile that closely resembles traditional meat [73].

In summary, while significant progress has been made in understanding and mitigating off-flavors in plant-based meat analogues, challenges remain. The complexity of flavor formation mechanisms and the variability in consumer preferences make it difficult to develop a one-size-fits-all solution. Additionally, the demand for clean-label products necessitates the development of natural and minimally processed solutions for flavor improvement. Future research should focus on exploring novel processing techniques and leveraging advances in biotechnology, such as genome editing, to further enhance the flavor profiles of plant-based meat analogues.

Achieving Nutritional Equivalence and Completeness

Achieving nutritional equivalence and completeness in plant-based meat analogues involves replicating the nutritional profile of traditional meat products while also addressing health, environmental, and sensory considerations. The development of plant-based meat analogues is driven by the need for sustainable protein sources that align with ethical and environmental goals. However, achieving nutritional equivalence with traditional meat products presents several challenges and opportunities.

- Nutritional recommendations and challenges: A Delphi study established 12 nutritional recommendations for plant-based meat analogues, focusing on limiting sodium and saturated fats while ensuring adequate intake of essential nutrients like proteins, fiber, vitamins, and minerals. These guidelines aim to support the food industry in creating nutritionally balanced plant-based meat analogues that meet consumer expectations for health and sustainability [74]. Despite efforts to mimic traditional meat, plant-based meat analogues often lack essential micronutrients such as iron and vitamin B_{12}, which are naturally abundant in animal products. This gap highlights the need for fortification and innovative ingredient use to achieve nutritional completeness [75].

- Comparative nutritional analysis: Plant-based meat analogues generally have lower saturated fat, cholesterol, and sodium levels compared to traditional meat products, offering potential cardiovascular benefits. However, they may also have higher energy and fat content, depending on the formulation [76, 77]. Plant-based meat analogues can provide comparable protein content to traditional meats, with some formulations offering higher fiber content due to the inclusion of plant-based ingredients like legumes and grains [77, 78].

- Ingredient innovation and processing: The use of diverse plant proteins, fibers, and polyphenolic compounds can enhance the nutritional profile of plant-based meat analogues. These ingredients not only contribute to nutritional value but also improve the texture and sensory attributes of the products [21]. Advanced processing methods, such as high-moisture extrusion and protein blending, are crucial for developing plant-based meat analogues with meat-like textures. These techniques also influence nutritional quality by affecting protein digestibility and bioavailability [52, 79].

- Environmental and market considerations: Plant-based meat analogues have a significantly lower environmental impact compared to traditional meat, with reduced greenhouse gas emissions and resource usage. This makes them an attractive option for environmentally conscious consumers [78, 79]. While plant-based meat analogues offer nutritional and environmental benefits, sensory attributes such as taste and texture remain critical for consumer acceptance. Studies indicate that plant-based meat analogues often fall short in sensory evaluations compared to traditional meat products, necessitating further research and development to enhance their appeal [80].

In summary, while plant-based meat analogues present a promising alternative to traditional meat products, achieving nutritional equivalence and completeness requires addressing micronutrient gaps, optimizing ingredient use, and improving sensory attributes. The development of plant-based meat analogues must balance nutritional quality with consumer preferences and environmental sustainability to fulfill their potential as a viable meat substitute.

Consumer Acceptance: The Pivotal Role of Sensory Experience

The sensory experience of plant-based meat analogues plays a crucial role in consumer acceptance, as these products aim to replicate the sensory attributes of traditional meat. The success of plant-based meat analogues in the market largely depends on their ability to mimic the taste, texture, and overall sensory profile of meat, which are key determinants of consumer satisfaction and acceptance. This section explores the role of sensory experience in consumer acceptance of plant-based meat analogues.

Importance of sensory attributes

- Taste and flavor: Taste is a primary factor influencing consumer acceptance. Plant-based meat analogues often struggle to replicate the umami and meaty flavors of traditional meat, which are highly valued by consumers. Studies indicate that plant-based burgers often score lower in meaty aroma and flavor compared to animal-based burgers, which affects their acceptability [81, 82].

- Texture: The texture of plant-based meat analogues, including attributes like juiciness, elasticity, and firmness, is critical. Many consumers find plant-based products lacking in these areas, which can lead to lower acceptance. For instance, plant-based meat analogues often lack the juiciness and cohesiveness found in meat, which are important for a satisfying eating experience [64, 81].

- Appearance and smell: Visual appeal and aroma also significantly impact consumer perceptions. Plant-based meat analogues need to closely resemble meat in appearance and smell to attract non-vegetarian consumers. The sensory evaluation of plant-based meat analogues often highlights deficiencies in these areas, which can be a barrier to acceptance [64, 83].

Strategies for enhancing sensory experience

- Product development and innovation: To improve sensory attributes, manufacturers are employing innovative processing techniques and blending various plant protein sources. These efforts aim to enhance the taste, texture, and overall sensory profile of plant-based meat analogues [5, 58].

- Sensory evaluation and testing: Conducting sensory evaluations, including hedonic tests and descriptive analysis, helps in understanding consumer preferences and improving product formulations. These evaluations provide valuable insights into the sensory attributes that need enhancement [82, 83].

- Cooking methods: The type of cooking method can influence the sensory attributes of plant-based meat analogues. For example, certain cooking techniques can enhance the flavor and texture of plant-based meat analogues, making them more appealing to consumers [58].

Consumer preferences and market trends

- Target demographics: Younger, educated, and environmentally conscious consumers are more likely to accept plant-based meat analogues. These groups often prioritize health and environmental benefits over sensory attributes, although the latter remains important [84, 85].

- Cultural and demographic differences: Acceptance of plant-based meat analogues can vary based on cultural and demographic factors. Understanding these differences is essential for tailoring products to specific consumer segments [64, 85].

While sensory experience is a critical factor in consumer acceptance of plant-based meat analogues, it is not the only consideration. Other factors, such as health benefits, environmental impact, and ethical concerns, also play a significant role in shaping consumer attitudes. However, for plant-based meat analogues to become mainstream, they must overcome sensory challenges and meet consumer expectations for taste, texture, and overall eating experience. Addressing these sensory gaps through innovation and targeted product development can significantly enhance the market potential of plant-based meat analogues.

Case Studies

The development of plant-based meat analogues is a rapidly evolving field driven by environmental, health, and ethical considerations. These products aim to replicate the sensory and nutritional qualities of conventional meat using plant-derived ingredients. Recent studies have focused on optimizing formulations, processing techniques, and ingredient selection to improve the quality and consumer acceptance of these analogues.

A study [52] utilized a multiscale approach, including atomic force microscopy-based infrared spectroscopy and X-ray microscopy, to visualize the high-moisture extrusion process for converting peanut protein biomass waste into meat substitutes. The key results highlight the structural changes of proteins and the formation mechanism of the meat-like fibrous structure. Protein molecules underwent significant structural changes and unfolded within the extruder barrel. This unfolding created favorable conditions for molecular rearrangement in subsequent processing zones. The formation of the meat-like fibrous structure began at the junction of the die and the cooling zone. This fibrous structure was attributed to the phase separation and rearrangement of protein molecules occurring within the cooling zone. Hydrogen bonds and disulfide bonds formed in the cooling zone were crucial for maintaining the meat-like fibrous structure. The stable fibrous structure exhibited a secondary structure composition primarily characterized by α-helix > β-sheet > β-turn > random coil. Among the two primary peanut proteins, arachin played a more significant role than conarachin in forming the fibrous structure. Specifically, arachin subunits with molecular weights of 42, 39, and 22 kDa were identified as particularly important for fibrous structure formation. In summary, the research provides a detailed understanding of how peanut protein transforms during high-moisture extrusion, revealing the critical stages of protein unfolding, fibrous structure initiation, and the molecular interactions and specific protein components responsible for its formation.

A study by Zahari et al. [86] investigated the potential of industrial hemp to replace soy in high-moisture meat analogues using extrusion cooking. The key results highlight the feasibility of using hemp protein concentrate and its impact on the product's characteristics. It was found possible to extrude a mixture containing up to 60% hemp protein concentrate in high-moisture meat analogues (Figure 1). This indicates that hemp protein concentrate can successfully substitute a significant portion of soy protein isolate. Hemp protein concentrate showed different properties compared to soy protein isolate. Specifically, hemp protein concentrate absorbed less water and required a higher temperature for denaturation than soy protein isolate. These differences in fundamental protein characteristics likely influence the extrusion process and final product texture. An increase in moisture content by 5% was projected to lead to a reduction in both hardness and chewiness of the resulting high-moisture meat analogue product. This suggests that moisture levels are a critical parameter for controlling the textural attributes of these plant-based analogues. The lightness (L^* value) of the high-moisture meat analogues product was significantly higher in products made primarily with soy protein isolate. Conversely, the lightness decreased as the proportion of hemp protein concentrate in the mixture increased ($p < 0.05$). This indicates that hemp protein concentrate contributes to a darker product color. In summary, the study successfully demonstrated the technical feasibility of incorporating industrial hemp protein into high-moisture meat analogues, offering a potential alternative to soy protein, particularly for regions where soy cultivation is challenging. However, the substitution level of hemp protein concentrates influences key product attributes such as water absorption, denaturation temperature, and color, which need to be considered during product development.

A study by Xia et al. [87] on meat analogues from *Haematococcus pluvialis* residue-pea protein reported successful extrusion with *H. pluvialis* residue (Figure 2). Mixed raw material containing *H. pluvialis* residue in concentrations ranging from 10 g/100 g to 40 g/100 g successfully underwent high moisture extrusion at 50 g/100 g moisture content. This indicates *H. pluvialis* residue's viability as an ingredient in this process. The natural reddish color of *H. pluvialis* residue imparted a resemblance to dried red meat in the extrudates, which could be a desirable characteristic for meat analogues. *H. pluvialis* residue significantly enhanced the textural properties of the meat analogues by promoting a loose layered and fibrous structure. The maximum fibrous degree of 1.28 ± 0.05 was achieved with a 10 g/100 g (dry basis) *H. pluvialis* residue content. Even at a higher *H. pluvialis* residue content of 40 g/100 g (dry basis), the fibrous degree remained elevated at 1.15 ± 0.03, surpassing that of extrudates without *H. pluvialis* residue (1.08 ± 0.05). The improved texture in meat analogues with *H. pluvialis* residue was primarily attributed to an increase in free water content and the formation of β-sheet structures within the extrudates. In summary, the study demonstrates that *H. pluvialis* residue can be effectively incorporated into pea protein-based meat analogues via high moisture extrusion. Its inclusion not only provides a desirable reddish color but also markedly improves the textural properties, specifically the fibrous

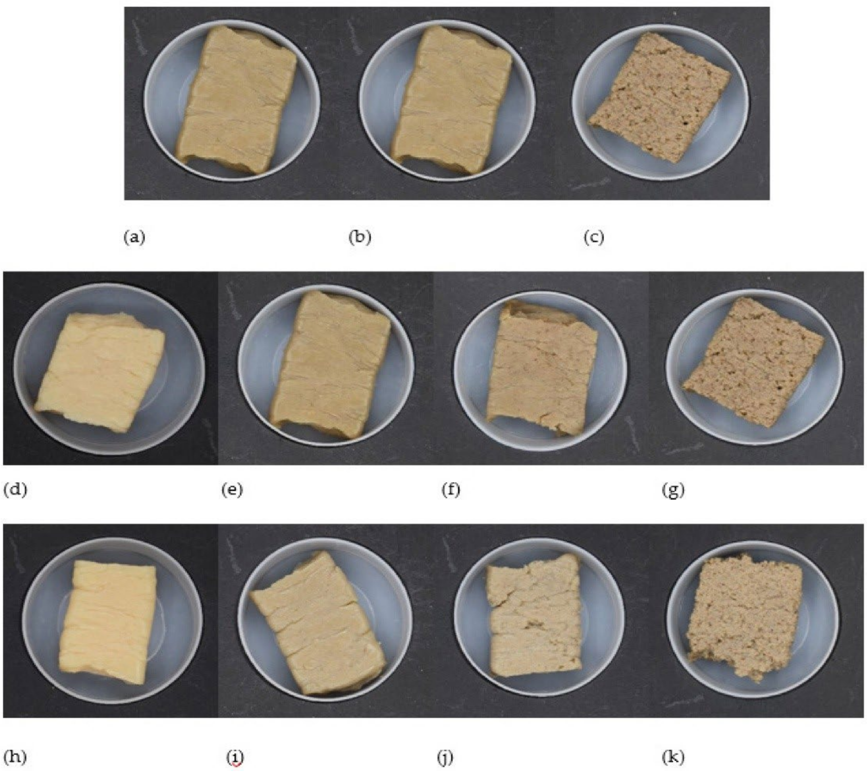

Figure 1: The images display extruded meat analogues produced under different conditions. The variables are the percentage of hemp protein concentrate (ranging from 0% to 60%) and the target moisture content (65%, 70%, and 75%). For example, images **(a-c)** show samples with 20% to 60% hemp protein concentrate at 65% moisture, while images **(h-k)** show samples with 0% to 60% hemp protein concentrate at 75% moisture [86].

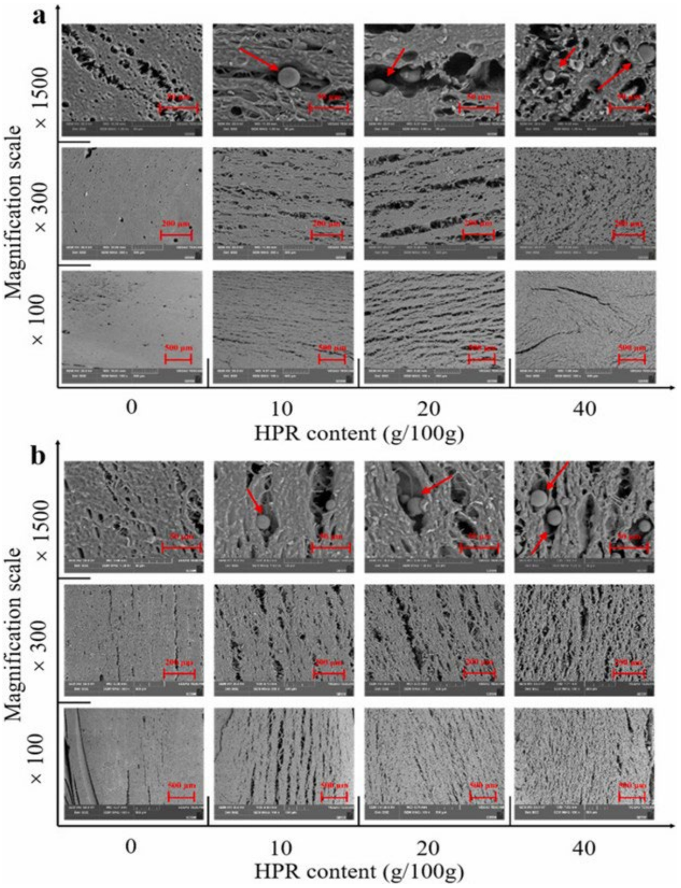

Figure 2: Scanning electron microscope images of the meat analogues in **(a)** transverse section and **(b)** longitudinal section [87].

degree, by influencing the internal structure and water content of the extrudates.

A study by Bakhsh et al. [88] compared the physicochemical, textural, and sensory properties of plant-based meat analogues with those of beef and pork patties. The findings reveal distinct differences and some similarities across these categories. Meat analogues patties exhibited significantly lower moisture, fat, and protein content compared to both beef and pork patties. Conversely, meat analogue patties had substantially higher ash and crude fiber content than beef or pork patties. This higher fiber content in meat analogues is attributed to the plant-based ingredients and polysaccharides used in their recipe. The lower moisture loss in meat analogue patties is likely due to the incorporation of methylcellulose, which forms an adhesive layer during heating, preventing moisture loss through thermal gelation. Meat analogues patties showed higher pH values both before and after cooking compared to beef and pork patties. This is likely due to the slight alkalinity of textured vegetable protein, the base for meat analogues. Meat analogue patties generally had lower lightness and redness values compared to beef and pork, especially before cooking. The yellowish coloration of meat analogue patties is associated with the yellow color of soy protein ingredients. Meat analogues patties displayed the highest values for released water and cooking loss, indicating lower water retention compared to beef and pork. The higher concentration of soy-based water-soluble proteins and the porosity of textured vegetable protein structure contribute to this. All patty types showed significant diameter reduction post-cooking. Beef and pork experienced higher shrinkage due to connective tissue denaturation and fluid loss, while meat analogue patties, though showing reduction, had less shrinkage compared to beef. Meat analogue patties were significantly less tough than pork or beef, with lower Warner-Bratzler shear values. This suggests softer textural properties for meat analogues. Beef patties exhibited significantly higher hardness, chewiness, and gumminess than both pork and meat analogue patties. This is linked to muscle protein denaturation in meat. While cohesiveness and springiness varied by patty type, the differences were not statistically significant. Meat analogues patties received higher scores for appearance and firmness in sensory evaluations compared to beef and pork. The overall acceptability of meat analogues patties was comparable to beef and pork, with no significant statistical difference. The study noted that no 'beany' essence was detected in meat analogues patties, likely due to the plant-based ingredients used to mask such flavors. In summary, the study highlights that while meat analogues patties differ from beef and pork in their proximate composition, pH, and water-holding capacity, they can achieve comparable sensory acceptability and exhibit softer textural properties. Further research is needed to refine meat analogues formulations to more closely mimic the textural and sensory profiles of traditional meat products.

A study by Chen et al. [89] investigated the rheological properties of pea protein isolate mixed with amylose/amylopectin and their application in high-moisture extruded meat substitutes. The consistency coefficient (K) and flow behavior index (n) for pea protein isolate-amylose/amylopectin mixtures varied significantly based on the ratio. For instance, a 0:1 amylose/amylopectin ratio resulted in a K value of 221.78 ± 5.80 ($x10^{-3}Pa \cdot s^n$) and an n value of 0.08 ± 0.01. In contrast, a 1:2 ratio showed K = 24.77 ± 2.13 and n = 0.37 ± 0.00, while a 1:0 ratio (pure amylose) had K = 230.73 ± 1.89 and n = 0.12 ± 0.00. The R^2 values for these fittings were generally high, ranging from 0.907 to 0.980. The die pressure during high-moisture extrusion was significantly affected by the amylose/amylopectin ratio. For the control (pea protein isolate only), it was 3.93 ± 0.06 MPa. The addition of amylopectin (0:1 ratio) reduced it to 3.27 ± 0.06 MPa, and a 1:2 ratio further decreased it to 3.10 ± 0.10 MPa. The lowest die pressure was observed at a 2:1 ratio, with 2.60 ± 0.10 MPa. Motor torque also varied significantly. The control registered 143.00 ± 0.00 Newton-meters (N·m). The 0:1 ratio showed 140.33 ± 0.58 N·m, and the 1:2 ratio had 142.00 ± 0.00b N·m. The 2:1 ratio resulted in 142.33 ± 0.58 N·m. Specific mechanical energy for the control was 985.07 ± 5.49 kJ/kg. The 0:1 ratio yielded 969.72 ± 10.70 kJ/kg, and the 1:2 ratio had 1010.54 ± 8.30 kJ/kg. The 2:1 ratio showed 959.44 ± 8.18 kJ/kg. The control extrudate had a lightness value of 48.70 ± 0.59. The 0:1 ratio increased lightness to 52.34 ± 0.72, and the 1:2 ratio showed 52.51 ± 0.81. The control had a redness value of 5.82 ± 0.35. The 0:1 ratio showed 5.77 ± 0.19, and the 1:2 ratio had 6.06 ± 0.25. The control had a yellowness value of 20.06 ± 0.39. The 0:1 ratio showed 21.25 ± 0.34, and the 1:2 ratio had 21.76 ± 0.72. The control had a color difference of 45.37 ± 0.58. The 0:1 ratio resulted in 42.62 ± 0.75, and the 1:2 ratio had 42.75 ± 0.66. The control extrudate had a hardness of 35.17 ± 3.53 kg. The 0:1 ratio significantly reduced hardness to 25.74 ± 1.17 kg, while the 1:2 ratio was 30.22 ± 0.97 kg. Control springiness was 96.02 ± 1.73%. The 0:1 ratio showed 87.86 ± 1.46%, and the 1:2 ratio was 90.14 ± 1.58%. Control chewiness was 26.83 ± 1.73 kg. The 0:1 ratio reduced it to 17.20 ± 1.06 kg, and the 1:2 ratio was 21.76 ± 1.41 kg. The control had a fibrous degree of 1.30 ± 0.01. The 0:1 ratio increased to 1.32 ± 0.01, while the 1:0 ratio (pure amylose) decreased it to 1.12 ± 0.06. The addition of amylopectin generally improved the degree of grafting. For the control (pea protein isolate only), the degree of grafting was approximately 0%. With a 0:1 amylose/amylopectin ratio, it was around 9.5%. As the amylose ratio increased, the degree of grafting decreased, for example, to about 7% for a 1:1 ratio and around 4% for a 2:1 ratio. The *in vitro* protein digestibility of the control pea protein isolate extrudate was 85.45 ± 0.45%. The addition of pure amylopectin (0:1 ratio) significantly decreased *in vitro* protein digestibility to 76.93 ± 1.34%. However, increasing the amylose ratio gradually improved *in vitro* protein digestibility, with a 1:0 ratio (pure amylose) showing an *in vitro* protein digestibility of 82.20 ± 0.81%. In summary, the study provides detailed statistical evidence showing that amylopectin generally improves fibrous structure and grafting, while amylose tends to create a more compact structure. Both amylose and amylopectin can reduce processing energy and improve color, but their specific ratios have distinct effects on textural properties and protein digestibility, with the 0:1 amylose/amylopectin ratio being advantageous for rich fibrous structures.

While plant-based meat analogues offer promising alternatives to conventional meat, there are still challenges to overcome in terms of improving their sensory and nutritional qualities, as well as consumer acceptance. Continued research and innovation in ingredient selection, processing techniques, and market strategies are essential to address these challenges and fully realize the potential of plant-based meat analogues.

Conclusion

The development of plant-based meat analogues that successfully satisfy consumer expectations is a complex; multidisciplinary endeavor centered on overcoming significant sensory and nutritional challenges. This review has detailed the considerable progress made in replicating the fibrous texture of meat through advanced processing technologies like high-moisture extrusion and shear cell technology, which facilitate the formation of anisotropic, myofibril-like structures. Concurrently, strategies for flavor profiling, particularly the mitigation of legume-associated off-flavors using biotechnological tools such as fermentation, are critical for enhancing palatability. Nutritionally, achieving equivalence requires careful formulation to ensure adequate protein quality and micronutrient content, often through the strategic incorporation of novel functional ingredients like algae and grape pomace. Despite these advancements, the ultimate benchmark for success remains consumer acceptance, which is overwhelmingly influenced by the product's ability to deliver a convincing and enjoyable sensory experience that mirrors conventional meat.

Looking forward, the future of plant-based meat analogues hinges on integrated and innovative research pathways. There is a pressing need to explore underutilized and sustainable protein sources and to refine processing techniques for better cost-effectiveness and scalability without compromising quality. Future efforts must also prioritize a holistic approach that seamlessly combines sensory appeal with nutritional completeness, potentially through the application of plant-based tissue engineering and other novel biotechnological interventions. By closing the remaining gaps in texture, flavor, and nutritional profile, the next generation of plant-based meat analogues can truly transition from a niche alternative to a mainstream component of sustainable and health-conscious global food systems.

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None.

Conflict of Interest

None.

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