



Advancements in Meat Analogs: Protein Selection, Flavoring, and Textural Enhancements

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Abstract

This paper provides a comprehensive review of key components used in the production of meat analogs, highlighting their roles and effects on the final product. The primary components discussed include plant-based proteins (such as soy, wheat gluten, and legume proteins), fats, binders, flavor enhancers, and colorants. Consumer acceptance of these products is influenced by factors such as taste, texture, appearance, and color. The functional properties of specific proteins like soy protein isolate and concentrate, wheat gluten, and pea protein are explored, focusing on their abilities in water retention, gelling, and emulsification. The use of plant oils is analyzed for their contributions to juiciness, tenderness, and flavor release. The complexity of flavoring during extrusion processing is discussed, considering the chemical interactions and changes that affect sensory stability. The role of binders, including protein-based and polysaccharide-based agents, is examined in relation to their impact on water and fat binding and texture enhancement. The importance of colorants, their thermal stability, and methods of application are also covered. Overall, optimizing these components to closely mimic meat's sensory attributes is crucial for consumer satisfaction. The review concludes with future directions and potential advancements in meat analog production.

Keywords: meat analogs, plant-based proteins, soy protein isolate, wheat gluten, legume proteins, binders, flavor enhancers, colorants.

Ingredients Composition in Meat Analogs

The selection of ingredients in meat analogs is critical for achieving desirable sensory properties. High water content not only reduces costs but also enhances juiciness by acting as a plasticizer during processing and aiding in emulsification. Adding protein for nutritional purposes does not immediately guarantee desirable texture, mouthfeel, or appearance. Therefore, textured proteins are often preferred. Meat substitutes can be produced through two pathways: one involves combining textured proteins with meat, resulting in hybrid products, while the other focuses on entirely replacing meat with textured proteins to create fully plant-based products[1-3].

While meat extenders may not resemble meat in appearance, texture, or mouthfeel when cooked alone, they can enhance the overall functional properties of the food product when mixed with meat. Conversely, hydrated and cooked meat analogs without any meat components can mimic the appearance, texture, and color of meat as a standalone product. Thus, specific compounds or chemicals can be used to enhance the final texture or assist in structuring the raw materials. Soy protein isolates and concentrates, wheat gluten, egg white, and other binding agents such as hydrocolloids and starches are essential in fine-tuning water-holding capacity, emulsification, and texture processing conditions. Flavorings and colorants are also employed to influence the taste and appearance, while the fat content can affect the aroma, color, and texture of the final product[4, 5].

Proteins

The growing interest in alternatives to animal-derived proteins has led to increased demand for plant-based proteins. This demand is driven not only by consumer trends but also by factors such as cost, availability, and suitability for incorporation into new products, with particular emphasis on their functional properties. Protein attributes such as water and oil-holding capacity, solubility, emulsification, foaming, and gelation are critical for structure formation in meat analogs. However, these functionalities depend on the type of protein, including its chemical composition, amino acid sequence, and secondary or higher-order structures. Environmental factors like pH, temperature, and ionic strength can alter protein structure and consequently its functionality[6, 7].

Currently, soy protein serves as the primary basis for most meat analogs due to its specific properties and low cost. Alongside soy protein, proteins produced via fermentation using various substrates and microorganisms have already been incorporated into meat analog production. The industrial production of meat analogs from protein-rich precursors, such as wheat, rice, corn, defatted oilseeds, cereal and legume flours, oil cakes, and derivatives (e.g., defatted soybean flour, soy protein concentrate, wheat flour), is under ongoing investigation. Novel potential protein sources, such as leaves and algae for textured protein, have not yet been extensively utilized in meat analog formulations[8, 9].

Soy Protein

Soy is widely used in meat analog formulations in the form of soy flour, soy protein concentrate, and soy protein isolate. Soy-based ingredients are popular due to their functional properties like water retention, gelation, fat absorption, and emulsification capability. Soy flour, the least processed soy product, comes in forms such as full-fat, defatted, and roasted. Defatted soy flour, produced by milling defatted soybeans, contains approximately 50% protein. Soy protein concentrate and isolate, which are rich in protein, are derived from defatted soybeans. Specifically, soy protein concentrate is produced through water-alcohol extraction, resulting in a product with about 70% protein. In contrast, soy protein isolate is obtained through alkaline extraction followed by precipitation at an acidic pH, yielding around 90% protein. The advantage of soy protein isolate, apart from its high purity, includes its light color and mild taste compared to other soy ingredients. However, for meat analog applications, extremely high protein purity is not always necessary, and the presence of additional components can sometimes be beneficial.[10-12].

Wheat Gluten

Wheat gluten is another commonly used protein in meat analogs. It has a natural capacity to form thin protein layers during stretching, which can easily convert into fibrous protein materials. This distinctive property results from the

molecular characteristics and mesoscopic behavior of wheat gluten. The disulfide protein bond is a critical feature of gluten, facilitating the development of a three-dimensional network, making it an essential ingredient for creating fibrous structures in meat analogs[13, 14].

Legume Proteins

Legume proteins derived from sources such as peas, lentils, lupins, and other beans have been studied for their functional properties, including emulsification, foam stabilization, and gel formation. Among them, pea protein is considered the most promising for meat analog applications, particularly when structured via high-moisture extrusion. However, pea-based structures are generally softer than soy-based products. Therefore, methods to enhance gel strength, such as modifying hydrogen bonding through the addition of chaotropic salts or optimizing processing conditions like temperature and protein particle size, are being explored. Studies have shown that proteins from peas, lentils, and lupins exhibit good emulsifying and foaming capabilities, although they tend to have weaker gelling capacities compared to soy proteins, except for pea protein. Some authors have suggested that breaking and additional pre-treatments of legumes can impact their gelation behavior[15-17].

Other Oilseed Proteins

Other interesting protein sources include canola and rapeseed, which are gaining attention due to their versatile functional properties and potential applications in food products, particularly in plant-based meat analogs. **Rapeseed proteins**, primarily composed of cruciferin and napin, have been noted for their excellent emulsifying and foaming capabilities. Cruciferin, a 12S globulin, contributes significantly to the stabilization of emulsions and foams due to its molecular structure, which allows it to form a stable interfacial layer around oil droplets or air bubbles. **Napin**, a 2S albumin, complements these properties by enhancing the stability and texture of foams, making rapeseed proteins valuable in various culinary applications. When subjected to high pressure and temperature, rapeseed proteins can undergo structural transformations that lead to gel formation. This gelation process is crucial for developing meat-like textures in plant-based products, as it mimics the fibrous and cohesive nature of animal muscle tissue. The ability to form such gels makes rapeseed proteins particularly suitable for creating plant-based analogs that require a firm, chewy texture. In addition to their textural benefits, **Napin** has been proposed as an extender for casein-containing products. This proposal is based on napin's ability to interact with β -casein, a major protein in milk, forming aggregates in solution. These aggregates are stabilized by various interactions, including hydrophobic, ionic, and salt-bridging forces. This aggregation can modify the functional properties of dairy products, potentially enhancing their texture, stability, and nutritional profile. **Canola proteins**, which primarily include albumins and globulins, also show promising functional properties. These proteins can form cohesive gels at lower salt concentrations, which is advantageous for formulating products with reduced sodium content. This gelation ability is due to the molecular composition of canola proteins, which facilitates the formation of a network structure that can trap water and other components, leading to a firm and stable gel. Moreover, when canola proteins are combined with **κ -carrageenan**, a well-known gelling agent, the resulting mixtures exhibit very strong and elastic networks. This synergistic interaction enhances the mechanical properties of the gel, making it suitable for applications where a robust and elastic texture is desired. The capacity of canola protein to act as a structural agent in various formulations highlights its versatility and potential as an alternative protein source in the food industry, especially in the context of developing new plant-based meat products that meet consumer expectations for texture and mouthfeel[18-22].

Fat Content in Meat Analogs

Currently available meat analogs are generally low in fat, as they are typically produced using defatted materials. However, the inclusion of fat or oil during processing significantly impacts the formation of fibrous structures. Previous studies have shown that extrusion processes with oil content exceeding 15% by weight can lead to lubrication of the material, negatively affecting the alignment of macromolecules. According to Sheftel et al. (1992), excessive lubrication can decrease the shear forces applied during extrusion, which are crucial for creating the desired fibrous texture in meat analogs. Despite these challenges, incorporating fat or vegetable oil in meat analog formulations offers several benefits. It can enhance juiciness, tenderness, crispiness, and flavor release, which are important sensory attributes for consumers of meat products. As such, protein materials, such as moderately defatted soy fractions containing their natural fat, have been introduced for the production of fibrous analogs. This approach can either replace or complement the addition of extraneous fat by mixing it with other ingredients in the final product formulation or by coating the meat-like structures. A variety of fats and oils are currently employed in plant-based meat analogs, including sunflower oil, canola oil, corn oil, palm oil, coconut oil, and soybean oil. The inclusion of fat or oil is considered essential as it can enhance the flavor profile of meat analogs by retaining volatile compounds, thus

contributing to a more satisfying taste experience. The choice of oil can also influence the texture and mouthfeel, as well as the nutritional profile of the final product, making it a crucial component in the formulation of high-quality meat alternatives[2, 23-28].

Binding Agents in Meat Analogs

Binding agents in meat analogs play a crucial role in ensuring the desired texture, stability, and overall quality of the final product. These agents can be derived from both animal and plant sources and serve to bind water and fat, creating a cohesive structure. Common binding agents include soy protein isolates and concentrates, wheat gluten, milk proteins, eggs, carrageenan, xanthan gum, and various other ingredients. Depending on the quantity used, some agents can function as both binders and extenders. High-protein materials primarily serve to bind water and form a protein network, while low-protein or non-protein ingredients like flours and starches generally act as fillers by physically trapping water and fat[29, 30]. The effectiveness of binding agents, including their concentration, quality characteristics, and nutritional properties, is under continuous investigation. Since the early 1980s, patents have been filed for compositions and uses of binding agents in textured products. For instance, Fabre patented the use of protein binders for textured proteins, comprising water or milk with 10-20% gluten, 10-20% whey protein, and 1-5% albumin. Similarly, Nguyen reported the use of wheat gluten and soy flour in chicken-like meat analogs. The concentration of binding agents directly influences the final product's characteristics. Aora et al. (2017) demonstrated the effects of carrageenan, soy protein concentrate, casein, and xanthan gum on mushroom-based sausage analogs containing 5% saturated fat[31, 32]. Wheat gluten, known for its adhesive and viscoelastic nature, is an excellent binder, enhancing dough development and leavening. Additionally, gluten reduces cooking loss during processing and preparation, improves slicing properties, and imparts desirable elasticity and chewiness. Another commonly used binder in meat analogs is egg white or albumin, which contributes to binding, increasing the product's protein content, and enhancing other physical and chemical properties. Similar to albumin, soy flour, soy concentrate, and soy isolate are frequently utilized. Soy isolate is particularly preferred due to its neutral flavor profile, lacking the characteristic beany taste of other soy products[31, 33]. Besides protein-based binders, polysaccharides such as pectin, guar gum, carrageenan, and cellulose are proposed for use in meat-like products as adhesives and enhancers. The gelling and thickening properties of polysaccharides, along with their ability to improve rheological properties and water-binding capacity, make them promising ingredients for meat applications. These polysaccharides not only help in forming the gel structure but also contribute to the overall mouthfeel and textural attributes, making them indispensable in the development of high-quality plant-based meat analogs[27, 34].

Flavoring Agents and Flavor Enhancers

The acceptance of meat analogs by mainstream consumers is heavily influenced by their taste and flavor profile. To impart a meaty flavor to these products, savory spices, meat seasonings, and salty aromas, along with their precursors, are commonly used. Additionally, iron complexes, such as ferric chlorophyllin or heme-containing proteins, are employed to enhance the meat-like qualities. However, flavoring these products during extrusion is a complex process due to the physicochemical changes that occur during processing. The chemical changes in raw materials during heating affect the aroma and spices added in the premix. Moreover, depending on the nature of these compounds, complex chemical reactions may occur. Under high temperatures and pressure, volatile components are released, leading to changes in flavor perception[35, 36]. Apart from the production process, maintaining the sensory stability of the product throughout its shelf life is equally important. Thermal treatment, along with changes in the sensory attributes of the product, enhances interactions between flavor components such as sugars, salts, and acidic compounds with the protein network, influencing the texture and structure of the product. For instance, chemical reactions like the Maillard reaction can generate new flavor compounds from sugars and amino acids. Among the generated aromas, roasted flavor is highly desirable, although there is a risk of off-flavor formation. Therefore, optimizing the flavor and perceived quality is a challenge, requiring high-quality raw materials and careful monitoring of aroma formation[37, 38]. Various precursors, such as reducing sugars (glucose, xylose, fructose, and ribose), amino acids (cysteine, cystine, proline, lysine, serine, methionine, and threonine), thiamine, and nucleotides, have been utilized to mimic these aromas in analog products. Chicken and beef flavors are produced from the same enzymatically hydrolyzed soy-based plant protein, influenced by reaction pH, while roasted, beany, egg, molasses, and apple-sauce-like aromas define optimal conditions for a hydrolyzed vegetable protein system with L-cysteine/D-xylose and a D-xylose/L-cystine system. These systems exhibit various sulfur-containing compounds, such as furans and thiophenes, which have strong meat-like aromas with very low threshold values. Similar observations were reported by Farmer and Mottram, and Hoffman and Schieberle, who found that the cysteine/ribose reaction is determined by sulfur-containing heterocyclic compounds, which are the main contributors to roasted and meat-like aromas[39].

Coloring Agents

Color and color changes are crucial characteristics of meat, making it essential for a meat analog to mimic these attributes. The protein materials used in meat analogs, such as soy protein and gluten, typically possess a beige or yellow-brown hue, which is lighter than the brown color of cooked meat and very different from the red of raw meat. Therefore, the use of colorants is vital, especially since the natural color of these proteins does not match the desired appearance of meat products. Currently, heat-stable colorants such as caramel, malt, annatto, turmeric, cumin, and carotene are used. Analogous to cooking meat, the conversion of nitrosylmyoglobin to nitrosylhemochrome causes a color change from red to pink at around 65°C. Meat analogs can benefit from similar color changes during cooking[40]. To achieve a color resembling both raw and cooked meat, a combination of heat-sensitive colorants and reducing sugars is employed, depending on the final product's characteristics. Heat-unstable colorants degrade at high temperatures, making it essential to choose appropriate colorants. Suggested colorants for meat analogs include betanin and beetroot extract. Additionally, reducing sugars can be added as browning agents, as they can react with protein groups (amines) in a Maillard-type reaction, mimicking the browning of natural meat. Several studies have reported that reducing sugars such as dextrose, maltose, lactose, xylose, galactose, mannose, and arabinose can be used for this purpose. These colorants are typically applied as coloring solutions that are mixed with plant proteins before the structural formation process, such as extrusion. Alternatively, the colorants can be mixed with protein-containing materials post-extrusion or injected into the barrel section of the extruder[41, 42]. Despite the availability of various coloring agents and methods, the color quality of meat analogs often falls short. This discrepancy can arise from the mismatch between the optimal pH of the colorants and the pH of the meat analog. A possible solution to this issue is to adjust the pH using acidic substances like citric acid, acetic acid, lactic acid, or their salts. However, this adjustment has limitations, as significant changes in pH can alter the structural properties of the protein and affect the final product's taste. Moreover, along with colorants, color retention aids such as maltodextrin and hydrated alginate are used to inhibit or control color migration from the structured and colored meat analogs[43, 44].

Discussion and Conclusion

The rising demand for plant-based meat analogs is driven by consumer concerns over health, environmental sustainability, and animal welfare. This exploration of meat analogs underscores the intricate balance required to replicate the sensory and nutritional qualities of traditional meat. A key focus is on the selection of appropriate plant-based proteins, fats, binders, flavorings, and colorants, each playing a crucial role in the final product's texture, taste, and appearance. Soy and wheat gluten are prominent protein sources, valued for their ability to form fibrous structures similar to meat. However, achieving the right texture requires precise control of the extrusion process and careful balancing of ingredients. The inclusion of plant oils enhances mouthfeel and flavor but poses challenges in maintaining product structure and stability, particularly under high-temperature processing conditions. The choice of binders, ranging from protein isolates to polysaccharides, significantly impacts the cohesiveness and moisture retention of the product, essential for replicating meat's juicy texture. Flavor and color are critical sensory attributes that influence consumer acceptance. The complex interactions of ingredients during processing can lead to both desirable and off-flavors, necessitating the use of advanced flavor technology and natural additives. The challenge of achieving a meat-like color is addressed through natural colorants and the Maillard reaction, which simulate the appearance of cooked meat. However, maintaining consistent color stability remains a challenge, particularly under varying pH conditions. In conclusion, the creation of meat analogs is a multidisciplinary endeavor that requires innovation in food science and technology. Future advancements should focus on refining the sensory qualities, improving nutritional profiles, and ensuring product safety and stability. As the market for plant-based alternatives continues to expand, ongoing research and development will be critical to meeting consumer expectations and promoting a sustainable food future.

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