ACS FOOD SCIENCE & TECHNOLOGY

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Review

Shear Cell Technology and the Role of Ingredients in Developing Fibrous Plant-Based Meat Analogs

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Cite This: *ACS Food Sci. Technol.* 2025, 5, 2877−2891

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ABSTRACT: The increasing demand for sustainable protein sources has driven significant interest in plant-based meat analogs (PBMAs). However, replicating the fibrous texture of conventional meats remains a major challenge. Shear Cell Technology, an emerging thermomechanical processing method, has shown promise for the development of anisotropic fibrous structures by applying controlled shear forces to plant proteins. Unlike high-moisture extrusion, this method operates under moderate shear conditions with lower energy input, enabling better control over texture and structure formation. This review explores the influence of Shear Cell Technology on the production of plant-based meat analogs (PBMA). This highlights the role of key ingredients, particularly proteins, hydrocolloids, and lipids, in achieving desirable structural and sensory properties. It also discusses the recent innovative approach based on well-defined shear flow that can produce fibrous, anisotropic structures from plant-based biopolymers using either a cone−cone device (Shear Cell) or a concentric cylinder device (Couette Cell). This innovative method creates fibrous structures under moderate conditions with low shear forces, resulting in a low specific mechanical energy input. Hence, this review provides insight and knowledge about shear cell technology as well as the significance of ingredients in structure development.

KEYWORDS: *shear cell technology, fibrous structure, plant protein, plant based meat analog*

1. INTRODUCTION

Meat analogs are food products that resemble meat in terms of appearance, flavor, and texture. In simpler terms, a food product structurally similar to meat but with a different composition is called a meat analog.[1] These products, often called imitation meat, mimic meat, fake meat, or meat replacements, are commonly used to replace meat in diets. In recent years, the market for animal meat has been limited because of rapid population expansion, animal illnesses, environmental issues, possible disease concerns (such as diabetes, obesity, and cardiovascular disease), and production expenses, which have led to a trend toward the development of meat alternatives.[2,3] As per the Root Analysis Business Research and Consulting, the size of the global market for plant-based meat is expected to increase from $17.1 billion in the year 2024 to $54.8 billion by 2035 at a compound annual growth rate (CAGR) of 11.16%. Meat analogs are gaining popularity as healthier and more sustainable alternatives to meet the growing demand for meat, projected to feed 9.8 billion people by 2050.[4] Meat analogs can be divided into three primary groups according to their source: cell-based (in vitro or cultured meat), plant-based, and fermentation-based (mycoproteins).[5] Cultured cell meat was created in vitro conditions using animal cells. Cultured meat is sometimes referred to as lab-grown or cultivated meat because it is manufactured in a laboratory. It is used to reduce animal slaughter and promote a sustainable global food system. In 2018, a study found that cultured meat reduced greenhouse gas emissions and used less water and land.[5] However, the key issues with cell-cultured meat include poor cooked meat quality, rigorous cultivation conditions, high costs, high public opinion values, and low customer acceptance. In addition, plant-based meat substitutes provide a foundation for industrial manufacturing, and possibilities for market expansion.[6] Figure 1 highlights the different stages involved in the development of plant-based meat analogs. The structural arrangement of plant-based meat substitutes depends on their protein characteristics, including gelation, solubilizing capacity, and liquid retention.[7] However, the texture or fibrous structure is the main problem in the development of meat substitutes. Innovation in fibrous plant-based meat preparation has emerged as a significant area of research in recent years. The use of various protein texturizing methods has been thoroughly studied over time to create meat substitutes or analogs.[8] These plant-based meat analogs are structured using either bottom-up or top-down techniques. Individual structural components are made using the bottom-up approach, and these are then combined to build larger products. Bottom-up strategies include spinning technologies such as wet spinning and electrospinning, as well as in vitro cell culture methods.[9] In electro spinning, a polymer solution is forced through a hollow

Received: April 28, 2025
Revised: July 8, 2025
Accepted: July 8, 2025
Published: July 16, 2025

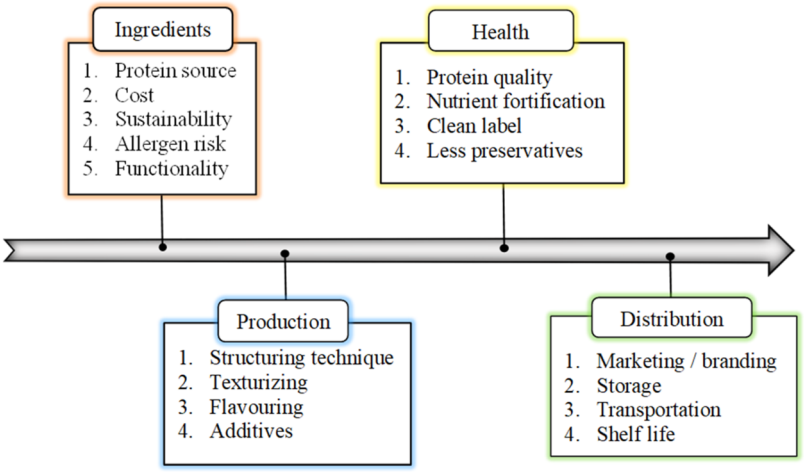

Figure 1. Roadmap outlining the different stages involved in the development of PBMAs. This infographic gives step-by-step guidance describing the important parameters for each phase of PBMA manufacturing and distribution.

needle with a high electric potential relative to a ground electrode. This process causes surface instabilities in the droplet, which leads to the creation of fibers that are attracted toward the ground electrode. Whereas in wet spinning is the process of extruding a polymer solution into a coagulation bath, where fibers are allowed to solidify as they come into contact with the coagulant. This process depends on the combination of the spinning material and the coagulation solution to generate continuous fibers. However, these techniques are very difficult because they utilize huge volumes of water or organic solvents, and upscaling presents a hurdle.

Top-down methods use blends of biopolymers whose fibrous structures are formed after stretching. The top-down strategy helps mimic the meat structure on relatively larger scales when compared to the bottom-up strategy. Several well-established techniques are used to produce the structure of fibrous plant protein components using the top-down approach, including extrusion and freeze structuring methods.[10] Extrusion is now the most commonly used approach for this purpose, owing to its simplicity and ease of scaling. Proteins and polysaccharides are combined with water during extrusion and then heated and delivered through the device under high pressure.[11] These conditions stimulate protein unfolding, aggregation, and structuring, resulting in fiber-like structures. However, extrusion requires the use of expensive machinery with significant energy input requirements. These disadvantages increase manufacturing costs and limit access to small-scale food businesses. Furthermore, the possible fiber structures are limited. Freeze structuring creates fibrous textures in meat analogs by freezing protein emulsions. As ice crystals grow, they align proteins and other components, forming layered structures. The ultimate texture is determined by ingredient interactions and freezing conditions. Although these top-down techniques can replicate meat structures of greater size, the resulting structures do not entirely reflect their hierarchical design. Commercial plant-based protein meat can effectively reproduce the fiber flavor of many animal meat products, but there are still some concerns regarding the overall texture and quality. Thus, a new approach was developed to solve the aforementioned scientific gap based on simple shear flow.[12] Similar meat-like fibrous structures can be created using the Shear Cell Technology.[13] The presence of two immiscible phases in plant materials that align during shearing increases the likelihood of fibrous materials in the shear cells. Shear cell technology involves mixing and hydrating the raw materials before processing. To create a fibrous structure, the doughy mixture was placed in a shear cell and subjected to specific thermomechanical treatments.[14]

This review provides an overview of high-pressure shear cell technology and its role in producing fibrous plant-based meat. It then examined the functionality of key ingredients, particularly protein sources, and their interactions with other components in the development of a fibrous texture. Finally, current trends, challenges, and future prospects for the commercialization of shear-cell-based plant-based meat alternatives are discussed.

2. SHEAR CELL TECHNOLOGY FOR THE DEVELOPMENT OF PLANT-BASED MEAT ANALOGUES

2.1. Overview and Principle of Shear Cell Technology. Shear cell technology was established a decade ago, using well-defined shear flow deformation to produce fibrous materials. Shear cells were initially employed to investigate the effects of extrusion-like conditions on biopolymers such as starch and proteins. Later, shear cells were recognized as a new thermo-mechanical treatment method and a revolutionary structuring technology.[15,16] It is an innovative structuring technique that improves both the sensory experience and nutritional value. Both high moisture extrusion (HME) and shear cell technology use shear pressures to align biopolymers; however, the resulting structures have distinct macroscopic appearances.[3] The primary advantage of shear cell technology over extrusion methods is that shear conditions, such as shear rate and temperature, can be varied to create various product structures.[17] Cones can be cooled or heated using steam or a heating bath to elevate the processing temperature. This approach has an advantage over other extrusion technologies. It has been demonstrated that even dairy proteins can be fibrillized by shear cells.

The shear cell technology includes steps similar to HME, such as hydration, thermomechanical treatment, and cooling. The shear cell technique has been used to create anisotropic fibrous meat substitutes. To generate a meat-like fiber structure, it combines shear force with high temperature in the gap between cones, then cools and rests at room

https://doi.org/10.1021/acsfoodscitech.5c00416
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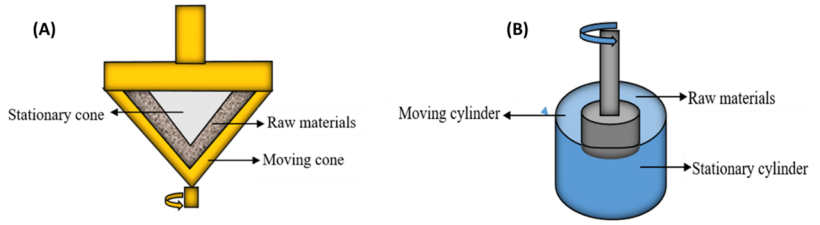

Figure 2. Systematic diagram of (A) Conical and (B) Couette shear-cell method (Imran et al.,[19]).

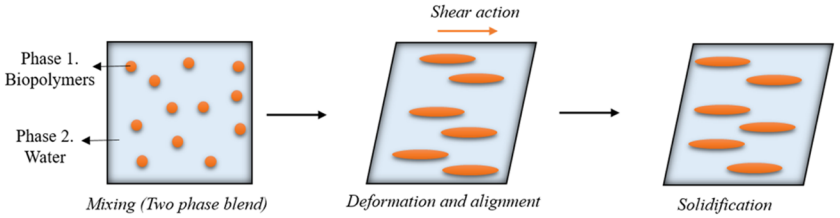

Figure 3. Schematic representation of Shear based structuring mechanism (Angonese et al.[24]).

temperature.[13] Additionally, shear cell technology may make PBMAs thicker than those made using HME techniques. This technology, which is still in the pilot stage, creates distinct product structures by creating a flow inside the product, which produces different fiber textures. Similarly, the shear cell approach requires significantly less mechanical energy than extrusion.

2.2. Components of Shear Cell Technology. There are primarily two types of shearing devices: cone-in-cone and Couette designs.[18] The conical device, also known as the shear cell, is composed of a rotating bottom cone and a fixed top cone, as shown in Figure 2A, and the other cone rotates to create shear.[19] The constructed shear cell utilized a cone−cone shape and adhered to the principle of cone−plate rheology. This batch procedure uses the same basic unit operations as HMEC. Dry ingredients were combined with water until they reached 50% to 70% moisture content, and then the mixture was sheared for approximately 30 min at temperatures between 90 and 140 °C.[4] To stop water vaporization at temperatures higher than 100 °C, the shear cell is closed. The cones were heated and cooled in an oil bath, and a thermocouple was used to measure the temperature within the cones during heating and cooling in an oil bath.[5] Cooling often occurs within the cell without shearing. In contrast to HMEC, fibrous structure creation in a shear cell occurs in a batch process with simple heating and no direct pressure.[13] This technology optimizes the energy usage and shear stress distribution of texturized items. Compared to extrusion cooking, the energy needed to rotate the outer cone and power the heating components or water/oil bath is less.[20] Thus, the use of a shear cell is frequently recommended as a viable substitute for extrusion because it allows greater control over the processing parameters. However, the cone-shaped design does not allow uniform shear stress throughout the material. Radial variations on the surface of the cone cause shear stress gradients and inhomogeneous results from the top to the bottom. As a result, the Couette Cell, a novel technique for plant-protein structuring, was developed.[20]

Couette cells (CC) employ shear stress to texture plant proteins, similar to concentric cylinder rheometers (Figure 2B). This involves the underlying idea of a similar concept in viscous fluid flow, in which two surfaces move tangentially to one another. The Couette Cell enables efficient shear deformation with minimal energy usage. Because shear stress is constant, the processed material experiences the same conditions.[20] The CC is made up of four basic parts: an outer stationary cylinder that may be axially moved with housing, a detachable lid to access the inner material, and an inner rotating cylinder that is attached to the shaft by a rheological unit to control the angular velocity of the spinning inner cylinder. The area between the outer and inner cylinders, where the plant proteins used for the sample were placed, is called the shearing zone. The Couette Cell is heated in a "hot" oil bath before and during an experiment, and it is cooled in a "cold" oil bath set at 60 °C following shearing.[20] The rheological unit controls the processing parameters, including pressure, torque response, and specific mechanical energy. Throughout the operation, a pressure of 7 bar was maintained and steam was employed as the heating medium.[21] Before placing the sample in the shearing zone, it was first premixed. Heat denatures the protein mixture, and a fibrous structure is formed by the velocity differential between rotatory and stationary components. The final result was determined by the composition and processing conditions of the mixture. The Couette cell design allows for an increased thickness and capacity by simply extending the diameter and length of the cylinders. Furthermore, in the future, the Couette Cell may be capable of operating in continuous mode. The following eq 1 provides the most basic approximation of the shear rate:

$$\gamma = \upsilon R_i/h \tag{1}$$

Where γ [s^{-1}] is the shear rate, υ_{R_i} [m/s] denotes the circumferential velocity of the inner rotating cylinder and h [m] is the space between the revolving and stationary cylinders

$$\upsilon_{R_i} = \Omega R_i = 2R_i\pi\frac{\mathrm{RPM}}{60}$$

where Ω [rad/s] is the rotational speed and R_i [m] is the radius of the inner cylinder.

2.3. Shear Cell Processing Steps in Structural Formation and Its Mechanism. Plant-derived proteins are generally processed to resemble the typical meat textures. Proteins from various plant sources, including soy, peas, and wheat, are extracted using a complex procedure to create

https://doi.org/10.1021/acsfoodscitech.5c00416
ACS Food Sci. Technol. 2025, 5, 2877−2891

PBMAs, which are then sheared into a fibrous texture. For HTSC structuring, it is commonly assumed that fibrous structure formation is caused by deformation of the biopolymer dispersion during shearing. The structure formation method in shear cell technology encompasses stages such as hydration, thermomechanical treatment, and cooling.[3] In other words, a simple combination of shear force and high temperature in the space between the cones, followed by cooling and resting at room temperature, can create a meat-like fiber structure as illustrated in Figure 3.[11]

The creation of fibrous structures in shear cell technology is determined by a critical synergy between component composition and processing step sequence. Proteins act as the principal structural agents; when hydrated, they unfold and become more mobile as depicted in Figure 4. During the shearing phase, the unfolded protein chains are mechanically aligned, revealing reactive regions like hydrophobic patches and sulfhydryl groups. Heating increases increased protein denaturation and aggregation, which aids in the creation of covalent (e.g., disulfide) and noncovalent connections required for network formation.[22] Polysaccharides affect viscosity and phase behavior, facilitating phase separation and domain alignment. Lipids operate as processing aids, boosting lubrication and moisture retention, but can interfere with matrix stability at high concentrations.[23] When cooled, the aligned protein structures solidify and fix, resulting in an anisotropic, meat-like texture. The efficiency of shear cell technology is dependent on the precise component-process interaction, which must be carefully adjusted to produce the necessary structural and sensory properties.

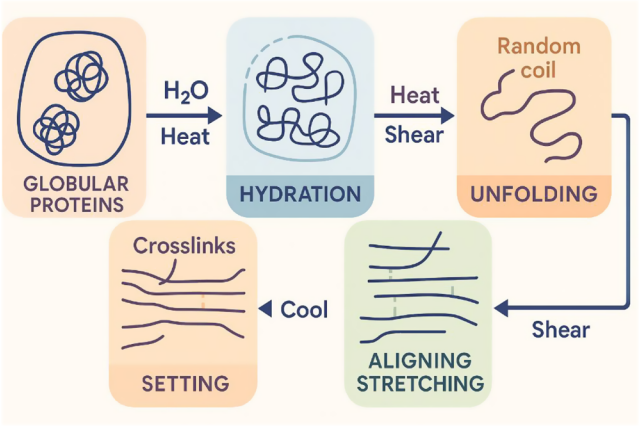

Figure 4. Schematic representation of the molecular and structural transitions during protein texturization in shear cell technology.

2.3.1. Mixing and Hydration. Mixing is a vital process in food processing. The initial stage of protein structure combines wet and dry materials to form dough.[15] It combines numerous components and modifies the structure of food products. Producing meat analogs from plant-based components using the shear cell method requires proper mixing and hydration.[25] In the case of HME, mixing occurs in the first section of the barrel and is intrinsically linked to thermomechanical treatment. In contrast, mixing in shear cell processing is always segregated from thermomechanical processing, because it occurs outside the equipment. The majority of the formulations employed NaCl, which was initially dissolved in water. Depending on the scale of operation (lab- or pilot-scale), a protein isolate or concentrate is blended with water using a Z-blade mixer or by hand with a spatula. After hydrating at room temperature for 30 min, an additional protein or polysaccharide was added, and the mixture was further combined to create a dough, which was then placed into the heated shearing apparatus and sheared.

Protein hydration is also a key step in shear cell processing. The hydration time after mixing may affect dough behavior in this procedure. When a protein blend is hydrated, water partitions into two phases. Time-domain nuclear magnetic resonance (TD-NMR) can measure water partitioning between proteins.[26] A variety of fibrous structures, such as layers, flaky structures, thick fibers, and small fibers, were produced by the use of various ingredient formulations and mixing conditions; combinations of these structural components were observed in certain products. The effects of mixing were determined by dough composition. For Soy Protein Concentrate (SPC), mixing had no effect on the rheological qualities of the dough or the visual and tensile test criteria. All mixing and hydration combinations revealed anisotropic structures in SPC. Prolonged mixing of soy protein isolate-wheat gluten (SPI-WG) produced a somewhat tougher dough, but it had no effect on the final product attributes. However, mixing had an impact on the quality of the final product.

2.3.2. Thermomechanical Treatment. After the process of mixing and hydration, a thermomechanical treatment is applied by applying heat and shear simultaneously. This combination is considered vital because the application of heat or shear alone does not produce a fibrous structure.[15] Thermomechanical reactions affect the rheological conditions of the material, causing conformational changes in proteins that alter their original configuration. Temperature is one of the process variables that has the greatest impact on protein structure. The intramolecular and intermolecular connections that maintain the protein structure are affected by temperature; when the temperature rises, hydrogen bonds weaken, and hydrophobic interactions may become more apparent. As the temperature rises, hydrogen bonds break and water molecules penetrate, causing protein chains to unfold gradually.[27] Furthermore, it disrupts intramolecular disulfide bonds and forms new intermolecular disulfide bonds. As the temperature increases, pre-existing intramolecular and intermolecular disulfide bonds become more unstable, and free thiol groups become more reactive.[28] Free thiol groups are created by alkali-catalyzed β-elimination of disulfide bonds upon heating. In addition, free thiol groups and unstable disulfide bonds can engage in thiol−disulfide interchange events, resulting in a transitory or reversible network. These thiol−disulfide interchange reactions may be facilitated by shear stress.[29,30] Disruption of the protein's stabilizing connections causes a change or loss of the basic protein structure, also referred to as denaturation.

When plant proteins are subjected to thermomechanical treatment, temperature and shear stress work together to cause phase separation and molecular alignment.[31] Proteins melt at high temperatures (usually above 130 °C), which destabilizes intramolecular and intermolecular interactions (such as hydrogen bonds and disulfide bridges) and increases protein mobility and unfolding.[32] At the same time, shear forces encourage protein chains to align along the direction of flow, exposing more thiol and hydrophobic groups that aid in cross-linking and interprotein interactions as the temperature drops.[33] The degree of phase separation between protein-rich and polysaccharide-rich domains is directly influenced by the

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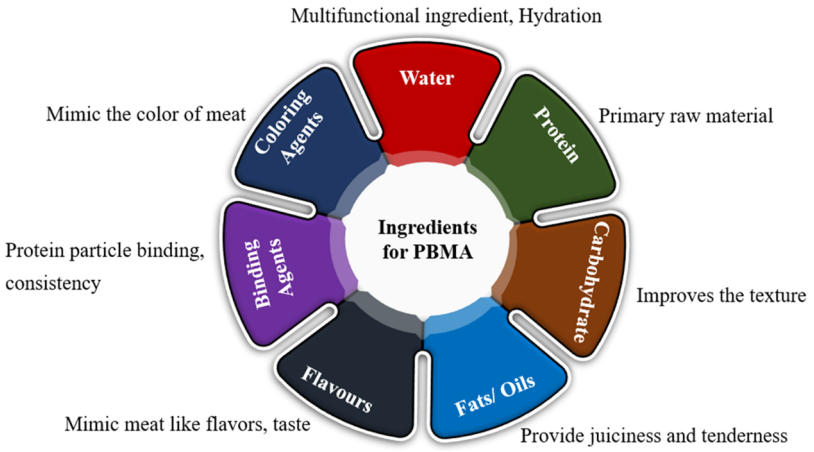

Figure 5. Pictorial representation of different ingredients and their functional role in developing PBMA.

viscoelastic behavior of the protein melt, which varies dramatically with shear velocity and moisture content, according to rheological experiments like those conducted by Schreuders et al.[31] Long, anisotropic domains are produced by this phase separation, and they solidify into fibrous structures when cooled.

It is assumed that dense protein dispersions reach a so-called molten state during thermomechanical treatment because of the weakening of the links between and within protein molecules.[34,35] Melt characteristics are significantly influenced by the connections between proteins, and disulfide bonds are considered crucial. The rheology of a proteinaceous melt is influenced by factors such as protein matrix, temperature, shear rate, water concentration, and fat/polysaccharide content. As the temperature increases, the flow velocity of the melts decreases owing to new protein−protein and protein−water interactions, causing the viscosity to rise. This stage is essential for the resulting product quality attributes, because these interactions influence the texture and sensory properties of the final product.[35] Fibrous structures require a melting temperature exceeding 130 °C. The degree of texturization increased as the melting temperature increased from 130 to 150 °C, indicating that the material had completely melted and that the protein−protein and protein−water interactions gradually improved.[2]

According to some research, thermomechanical energy alters those interactions that retain the protein's original structure, but it does not affect the main chemical bonds, including peptide bonds. However, the degree of texturization decreased, and the surface of the sample developed a brownish tint with microscopic pits when the temperature was increased from 150 to 160 °C. These results suggest that a comparatively greater temperature might cause intermolecular connections to dissolve, which would cause the protein to degrade.[36] To understand how a viscous melt transforms into a fibrous product, its rheological qualities must first be understood in depth.[37] Specific Mechanical Energy (SME) is an index used to quantify the mechanical energy imparted to an ingredient mixture. Melt viscosity is the initial effect of SME; a higher SME level results in a decreased melt viscosity and a greater melt temperature. The shear cell technique provides a well-defined shear flow during heating, allowing for a far lower mechanical energy input and the creation of a thicker, bigger product that resembles fibrous meat.[18] Furthermore, relatively mild process conditions, such as 95 °C and 30 rpm for 15 min at laboratory scale or 120 °C and 20 rpm for 30 min at pilot scale/for thicker products, can be employed to create a homogeneous, layered, and fibrous product from soy-gluten mixtures.

2.3.3. Cooling and Fiber Formation. Following the thermomechanical treatment, the melt was cooled. Cooling is crucial for the production of fibrous materials.[38] Cooling strengthens noncovalent interactions, making labile disulfide bonds permanent. Before the material completely hardens and the structure develops, cooling causes viscosity to increase. As the temperature decreases, the viscosity of the material increases, which may harden. If a transient network is present in the melt, it solidifies into a permanent network when cooled. Preventing the product from expanding as the shear cell opens is another reason for cooling. The solidified substance develops a gel or network of cross-linked polymers. The protein source and concentration, cooling rate, and heating temperature all affect gel properties. For instance, compared to soy protein isolates, pea protein isolates form weaker and less elastic gels.[39] Using shear during cooling can improve the structure formation by transferring mechanical forces to the two phases of the product during solidification. However, the application of an excessive shear force during cooling can cause structural failure. It was found that shearing during cooling could be used to create product structures that are different from those that are not sheared during cooling. Furthermore, cooling did not improve the development of a visible fibrous structure. The product structure is best described as "flaky." Compared to the products sheared during heating, those sheared during cooling were weaker. Thus, the creation of fibrous structures does not require deformation during cooling.[38]

3. POTENTIAL INGREDIENTS FOR THE DEVELOPMENT OF MEAT ANALOG

PBMAs use proteins (20−50%), polysaccharides (2−30%), and lipids (0−5%) that are biochemically comparable to those found in plants and animals. These components are crucial in defining texture, whereas other additives improve flavor, color, and nutritional content. In standard PBMA formulations, a protein, polysaccharide, and fat combination resembles a flesh texture, and protein isolates can be combined with carbohydrates, such as pectin or cellulose, to form fibrous structures. Additives, fats, and flavorings were added to improve the sensory appeal. On the other hand, flavorings, binding agents, texturizers, and coloring agents are essential for

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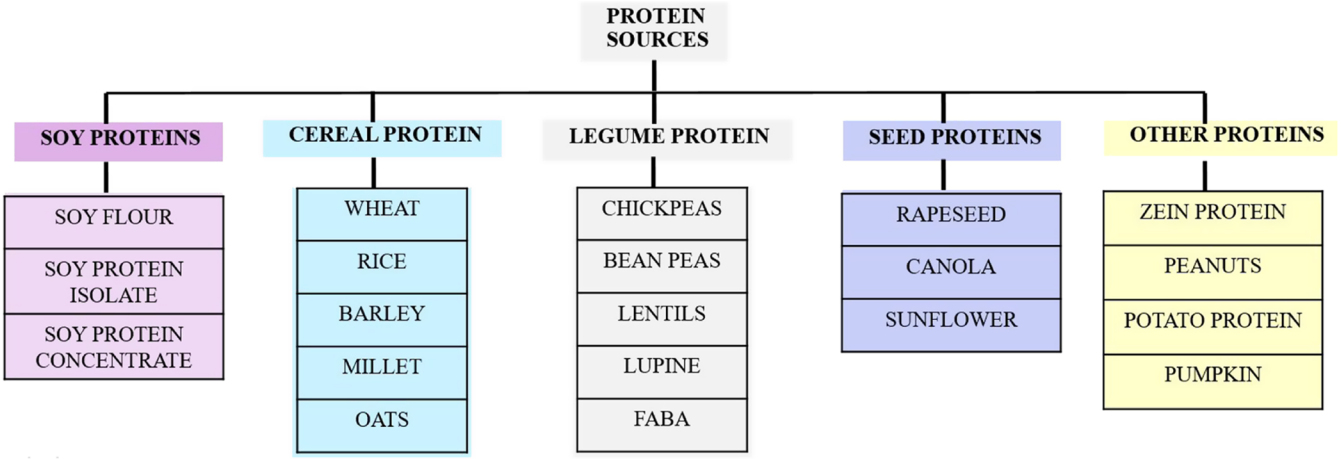

Figure 6. Protein sources for plant-based meat analog.

improving the product. Properly formulated meat analogs require precise amounts of ingredients and formulations to achieve the desired characteristics.[40] Figure 5 shows the necessary ingredients and their functional roles in the development of PBMA.

3.1. Role of Water in the Development of PBMA. Water is an important element in meat analogs because it provides hydration and aids in protein conformational changes. It also plays a significant role in the PBMA design. Water affects several functional properties of meat substitutes, including their viscosity, emulsifying ability, swelling index, gelling capacity, and foaming capacity.[34] Furthermore, water serves as a medium for the transfer of mechanical and thermal energy, and is essential for friction. Optimizing the water content to match the specifications of the raw materials is a crucial consideration. Water molecules hydrate biopolymer chains (proteins and soluble carbohydrates) by penetrating the protein matrix at a molecular level. Water breaks down protein−protein and carbohydrate-carbohydrate connections by forming hydrogen bonds with readily accessible polar amino acid side chains and carbohydrates, causing a plasticization effect.[41] Under certain temperature conditions, the shear force and pressure cause a transition to a melt-like state. Research indicates that a higher water content can improve the interactions between thiol bonds and hydrophobic interactions and between disulfide bonds and hydrogen bonds. At a moisture content of 55%, peptide chains become more flexible and align more because of the mobility enhancement of the protein structure. Water molecules promote the transition of α-helices to β-turns and β-sheets to random coils, reducing the temperature required to form the network.[2] In conclusion, water influences the association of polymers and melt viscosity by acting as a dispersion medium, plasticizer, and solvent.[42]

3.2. Role of Proteins in PBMA. Plant-based proteins have a considerable impact on the structure, color, texture, and flavor of meat analogs, in addition to their nutritional benefits, owing to their functional properties, such as solubility, emulsification, foam formation, and gelation. The four primary phases of conformational changes that a protein typically experiences are (I) molecular chain unfolding, (II) association, (III) aggregation, and (IV) cross-linking, in combination with oxidation and degradation processes.[18] Plant proteins are often categorized into three main groups according to their concentration: grits (usually soy, which has 50% protein content db), protein concentrates (70% db), and protein isolates (90% db).[2] Many plant-based proteins, including soy protein, wheat gluten, legume-based protein, and other seed proteins, have been utilized in the development of PBMA. (Figure 6)

Soy and pea proteins are widely used because of their availability, affordability, and processing adaptability. Owing to their low cost, effective gelation properties, and hydrophobic and hydrophilic amino acids that can interact with lipids or water to form a three-dimensional protein network, soy proteins are frequently used in the development of meat analogs. Furthermore, on the protein digestibility-corrected amino acid score scale, soybean protein had the highest possible score of 1.0. Recently, because of its strong beany flavor and high allergenicity, soy protein has been partially substituted by pea protein, resulting in fewer allergic products with improved hardness, chewiness, viscoelastic properties, and fiber structure.[43] Both protein molecules comprise globulin and albumin fractions, with approximately 90% of the latter containing 7S and 11S globulins.[44] These two subunits are primarily responsible for structural and functional changes in the protein, including solubility, gelation, emulsification, and foaming, under appropriate thermomechanical conditions. Soy proteins consist mostly of glycinin and conglycinin.,[40] whereas pea proteins contain legumin, vicilin, and convicilin. Glycinin (11S) appears to be more important for the texturization of soy proteins, whereas legumin (11S) is the major protein in peas. Soy protein has a higher proportion of the 11S fraction (glycinin), which forms disulfide bonds after cooling, making it more texturized than pea protein. However, the sole molecular reassociation of legume globular protein molecules is not sufficient to achieve fibrous texture and water binding capacity.[45] Soy proteins, specifically glycinin and β-conglycinin, have excellent gelation and cross-linking characteristics under heat and shear conditions, making them ideal for creating fibrous structures.[46] Glycinin (11S globulin) in soy is especially prone to generating disulfide bonds when cooled, which helps to preserve the aligned structure. Pea proteins, which largely comprise legumin and vicilin, exhibit weaker gelation and disulfide bonding, resulting in less elastic and fibrous networks. According to studies, soy-based combinations produce more defined, layered structures under shear cell conditions,[47] but pea-based formulations may require the addition of gluten or texturizing agents to increase fibrosity and strength (Table 1).

https://doi.org/10.1021/acsfoodscitech.5c00416
ACS Food Sci. Technol. 2025, 5, 2877−2891

Table 1. A Summary of the Various Functions Provided by Different Types of Soy Protein Components in the Creation of PBMA[40]

protein ingredients	composition (%w/w)	functionality	role
soy protein concentrate	∼70% protein	excellent texturization characteristics	protein source and texture binder
soy protein isolate	∼90% protein	high gelling, emulsification, and solubility abilities	protein source, texture binder, and emulsifier, the base for fat substitutes
defatted soy meal	∼43−56% protein, >30% carbohydrate, ∼0.5−9% fat, ∼3−7% crude fiber	increased water binding capacity	binder, texture stabilizing properties
spray dried soy milk powder	>45% protein, ∼30% fat	good solubility and high emulsification properties	binder, texture stabilizing properties

Wheat gluten (WG) accounts for approximately 80% of the total protein content in wheat and is also found in other grains, such as barley and rye.[48] WG develops when glutenins and gliadins combine with water and are subjected to mechanical stress.[49] It is widely acknowledged that gliadin functions as a plasticizer, adding to the viscosity and extensibility, whereas glutenin takes control of the synthesis of polymeric networks.[50] The main protein-based texturing agent for fibrous materials is WG, which promotes protein cross-linking and uses a disulfide exchange reaction to form a three-dimensional macromolecular network. WG is used as a thickener, fortifier, and texturizing ingredient in plant-based meat analog formulations because it helps create a strong and elastic gel that binds the fibers together, guaranteeing the strength of the finished product.[51] In conclusion, soy or pea protein is frequently mixed with WG and water (40−80%) to create the basic formulation used for shear cell technologies. Recently, there has been a shift toward substituting gluten because of its association with celiac disease. Suggestions have been made to substitute different proteins that mimic the characteristics of gluten by hydrolysis, fermentation, and inclusion of hydrocolloids.

3.2.1. Modification of Plant-based Proteins. Protein function encompasses unique roles and properties in many processes, including interactions with other molecules. Important considerations include solubility, emulsification, gelation, foaming, water-holding capacity, texture alteration, film-forming ability, heat stability, flavor interaction, and allergenicity. This causes plant proteins to face several obstacles to formulation and consumer adoption. It may be challenging to satisfy customer expectations for taste and mouthfeel owing to their unique flavors and textures when compared to animal-based proteins. Plant proteins such as soy and peanuts are known to cause allergies. Efforts have been made to improve plant protein functions by exploring various approaches and technologies. Various modification methods are required to enhance the functional properties. The term "protein modification" describes the process of using certain techniques to change a protein's molecular structure or a few chemical groups to increase its bioactivity and technological functionality. Plant-based proteins can be transformed into multifunctional elements in food systems by changing their physicochemical properties and overcoming their drawbacks (Table 2). Protein modification techniques can be classified as physical, chemical, biological, and other novel methods. Table 3 provides a summary of the different protein modification approaches and their associated modification characteristics.

3.3. Role of Polysaccharides in PBMA. The capacity to retain water and create stable oil/water emulsions is essential for achieving correct consistency and mouthfeel in PBMAs. This can be achieved by the addition of polysaccharides, which improves the functionality and structure of PBMAs. Saccharides are essential components of both natural and processed foods and provide texture and structure. Polysaccharide-based binders and fillers are used to improve the texture, help retain water, and possibly affect the viscosity of the mixture during processing, all of which are critical for the final product texture. Meat analog formulations have made use of natural polysaccharides, such as starch, pectin, carrageenan, and maltodextrin.[98,99] Polysaccharides from rice, peas, cassava, wheat, maize, and potatoes work well as fillers to enhance the consistency and texture of the PBMAs. Starch is a crucial component of PBMAs that influences product production, moisture retention, and texture modification.[100] High amylopectin starch types, such as wheat and maize starch, are especially good for providing PBMAs with the softness that is essential for imitating the bite and tenderness of meat. Proteins and hydrocolloids were combined during heat treatment under pressure to create fibrous structures. This caused the protein−polysaccharide mixture to deform and realign the two dissimilar biopolymer phases into an anisotropic fibrous structure.[101] When polysaccharides are added to a protein mixture, they can cause the Maillard reaction, hydrocolloid-protein interactions via hydrogen bonding, or hydrophobic and steric interactions.[102] This could affect network formation as well as the color and textural characteristics of the protein mixture when developing a meat analog. Therefore, it seems that the structure-texture relationship of the analogs created by the structuring process can be regulated by modifying protein−polysaccharide interactions in the food system. Hydrocolloids like methylcellulose, carrageenan, and pectin enhance water binding and heat stability in the protein matrix.[103] Under shear and heat, they contribute to the dough's viscoelastic behavior, assisting in phase separation between protein and polysaccharide domains.[104] This biphasic shape facilitates fiber alignment. Furthermore, hydrocolloids can interact with proteins through hydrogen bonding and electrostatic forces, improving matrix cohesion and textural integrity while cooling and setting (Table 4).

3.4. Role of Lipids in PBMA. To impart the sensory qualities of meat, such as juiciness, tenderness, and flavor release, oil or vegetable fat is most frequently used when making meat analogs. Fats are crucial PBMAs that replicate traditional meat juiciness, softness, and flavor characteristics. Lipid oxidation during heat processing creates flavor chemicals that improve meat-like taste.[105] In meat analogs, the inclusion of fat alters the alignment of proteins to create a fibrous structure. Plant-based oils, including coconut, sunflower, and avocado oils, are commonly used in PBMAs because of their health benefits compared to animal fats.[106] Plant-derived fats and oils have varying fatty acid compositions, including palmitic, stearic, oleic, caprylic, capric, lauryl, myristic, and

https://doi.org/10.1021/acsfoodscitech.5c00416
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Table 2. Different Sources of Protein Utilized in Meat Analog Formation and Their Functionality

proteins	structural characteristics	functionality	refs
soy protein	soy isolate and concentrate consist of β-conglycinin (7S protein) and glycinin (11S protein). 7S globulin is made up of three subunits, α, á, and β, each with a molecular weight of 67, 71, and 50 kDa, respectively. 11S globulin is a hexamer with four subunits. The acidic and basic subunits are connected by disulfide bonds.	emulsification, gelation, and aggregation, fiber formation	Kristiras et al.,[20] Krintiras et al.,[52] Tang and Wang[46]
pea protein	globulin, albumin, glutelin, and prolamin are the four main constituents of pea protein isolate and concentrate. Legumin (11S protein), a hexamer with a molecular weight of 320−380 kDa, Vicilin (7S protein), a trimer with a molecular weight of 150−170 kDa, and convicilin, which has a molecular weight of 290 kDa, are all present in globulin.	abundant in vital amino acids, having a strong gelation capability, good emulsion and oil absorption qualities.	Sägesser et al.,[13] Krintiras et al.,[52] Geerts et al.[47]
wheat protein	gliadin and glutenin are the two subunits that make up WG. Gliadins are monomeric proteins with a low to medium molecular weight that are connected by an intramolecular disulfide bond. Higher molecular weight glutenins are made up of several polypeptides connected by intermolecular bonds.	provide fibrous textures, chewiness, flexibility, and extensibility.	Peng et al.,[53] Gasparre et al.,[54] Krintiras et al.[52]
potato protein	potato protein is classified into three subunits: patatins (40−60% relative content, 40−43 kDa molecular weight), protease inhibitors (20−30%), and other high-molecular-weight proteins (10%).	used to improve the textural attribute	Schut et al.,[55] Nowacka et al.,[17] Imran et al.[19]
mung bean protein	mung bean protein is composed of four main subunits: globulin is a vicilin-type amino acid with a 60% relative content and a molecular weight of 26−60 kDa, albumins have a 25% relative content and a molecular weight of 24 kDa, gliadin, and glutelin.	excellent gelling characteristics promote ingredient binding and water retention. Albumins have superior textural stability; however, their qualities are temperature-dependent.	Tarahi et al.,[56] Angelis et al.,[57] Yi-Shen et al.[58]
zein protein	zein protein is made up of four major components: α zein (75 to 80% relative content and 19−22 kDa molecular weight), β zein (10 to 15% relative content and 14 kDa molecular weight), γ zein (10 to 15% relative content and 16−27 kDa molecular weight), and δ zein (10 kDa molecular weight).	zein protein has antioxidant and stabilizing properties. Zein-potato protein gives protein-based meat its gel-like consistency. Zein meat resembles chicken meat in both appearance and feel.	Mattice et al.,[59] Mattice et al.[60]
faba protein	faba protein is made up of four subunits: legumin (11S), a hexameric protein with a molecular weight of 300−400 kDa, vicilin (7s), a trimeric protein with a molecular weight of 150 kDa, albumin, polyamines, and glutelin.	good textural qualities, such as elasticity and firmness. Provides a tougher texture due to heavy minerals and low water holding capacity.	Saldanha do Carmo et al.,[61] Fan et al.[62]
hemp protein	the two main subunits of hemp protein are albumin has a molecular weight of 14−15 kDa and a relative content of 20−40%, while Edestin has a molecular weight of 60−80%.	hemp proteins are highly beneficial in emulsification, solubility, and oil and water retention capacity.	Zahari et al.,[63] Zahari et al.,[64] Imran et al.[19]
rice protein	globulin (salt-soluble, 12%, MW 12−20 kDa), albumin (water-soluble, 5%), prolamin (alcohol-soluble, 3%) fractions, and glutelin (alkali-soluble, 80%, MW 60−600 kDa) with subunits connected by disulfide bonds.	enhances the formation of structure; nourishment	Lee et al.,[65] Sha et al.[45]
rapeseed protein	approximately 90% of the proteins present in rape seed are storage proteins. Cruciferin and napin are the major storage proteins. The molecular weights are stated to be 300−350 and 12−16 kDa.	favorable functionality in terms of oil/water binding, gelling, and emulsifying qualities	Jia et al.,[14] Wanasundara et al.,[66] Chmielewska et al.[67]

https://doi.org/10.1021/acsfoodscitech.5c00416
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Table 3. A Summary on Various Modification Strategies of Plant Based Proteins and Their Associated Functionalities

techniques	description	modified characteristics	refs
conventional heat treatment	protein unfolding is encouraged by mild heat conditions, which results in an intermediate molten globule form with improved functioning. However, severe heat treatment results in irreversible protein structure changes, denaturing the proteins and causing them to aggregate through various bonds, such as hydrophobic, disulfide, and electrostatic ones, which reduces their functional qualities.	enhances the thermal stability, emulsifying and gel forming properties in protein sources such as soy, cow pea and album protein isolates.	Aryee et al.,[68] Avilés-Gaxiola et al.,[69] Mir et al.[70]
physical modification techniques			
high pressure	high hydrostatic pressure (HHP) is a nonthermal process that applies hydrostatic pressures between 100 and 800 MPa for a short period of time. HHP treatment was demonstrated to impact the denaturation, aggregation, and linkages of plant-based proteins.	HHP treatment normally raises the protein hydrophobic properties and decreases its solubility due to its ability to exposing hidden sulfhydryl groups after unfolding and denaturation, that is accompanied usually with improvement of its techno-functional properties	Lv et al.,[71] Liu et al.[72]
ultrasound (sonication)	a sustainable environmentally friendly method based on high sound waves (>16 kHz) that are undetectable to the human ear. The primary principles influencing protein structure are cavitation and shear pressures, which may break hydrogen, disulfide bonds and their free sulhydryl groups.	improved solubility and emulsifying capabilities. Reduced protein trypsin inhibitor activity, improved digestibility, and reduced allergenicity.	Sadaghat Doost et al.,[73] Wen et al.,[74] Garibzahedi et al.[75]
cold plasma (CP)	this method utilizes cold plasma, the fourth state of matter. Plasma treatment increases disulfide linkages in plant-based proteins, altering their secondary structure and rheological properties.	enhanced solubility, foaming and emulsifying ability, and water holding capacity, antioxidant characteristics.	Tolouie et al.,[76] Nikbakht Nasrabadi et al.,[77] Benković et al.[78]
pulsed electric fields (PEF)	this method involves exposing food samples to short, high-power electrical pulses (μs or ms) between electrodes. The PEF mechanisms can cause protein unfolding and promote interactions with solutes. This can increase protein solubility and impact its functional properties.	enhanced the isolated protein's solubility, emulsifying, and foaming qualities.	Zhang et al.,[79] Liang et al.,[80] Mahajan et al.[81]
chemical modification techniques			
glycosylation	also known as "glycation". Accomplished chemically through Maillard reactions or by cross-linking enzymes like transglutaminase or laccase. It occurs when a free amine group of a protein or amino acid covalently conjugates with the carbonyl group of a reducing sugar under regulated heating in the presence of water.	increased in bioactivity, solubility and emulsification properties.	Nasrabadi et al.,[82] Chen et al.,[83] Zhang et al.[34]
phosphorylation	the inclusion of phosphate groups into protein main sequences can significantly impact their functionality. Protein kinase is an enzyme that covalently bonds phosphate moiety to particular amino acid residues in proteins. This alters the protein's structure, affecting its stability and function.	enhanced apparent viscosity, thermal stability, emulsifying and foaming qualities, and solubility	Liu et al.,[84] Wang et al.[85]
acylation	the process of adding an acyl group to a protein by means of acyl anhydrides and halides. Acylation alters the secondary and tertiary structures of plant-based proteins, making them more hydrophobic while maintaining their nutritional value.	enhances the pea protein's water-holding capacity, emulsion stability, foaming qualities, and solubility.	Aryee et al.,[68] Zhao et al.,[86] Wang et al.[87]
deamidation	conversion of a protein's glutamine and asparagine residues' amide groups into carboxyl groups. Can be accomplished using a variety of techniques, including cation-exchange-resin treatment, enzymes, acids, and alkali.	reduces the allergenicity of proteins derived from plants, reduces bitter flavor of wheat gluten hydrolysates was reduced.	He et al.,[88] Abe et al.,[89] Nikbakht Nasrabadi et al.[77]
biological modification techniques			
enzymatic modification	most widely used techniques for protein modification because the reactants and byproducts are safe. This protein modification technique falls into two categories: enzymatic cross-linking and enzymatic hydrolysis. Because different enzymes have diverse mechanisms of action, their final products may differ in terms of functionality and properties. the most prevalent enzyme used for cross-linking is transglutaminase.	enhances mechanical strength, improves emulsifying and rheological qualities, increased capacity to store water and oil, and improved thermal characteristics	Nivala et al.,[90] Wouters et al.,[91] Xu et al.[92]
fermentation	conventional and cost-effective approach. plant proteins can be fermented using several starter cultures, including lactic acid bacteria, yeast, mold, and Bacillus strains. Lactic acid bacteria are the most commonly utilized.	improve soy protein solubility, water and oil holding capacity, and foaming properties. Enhance nutritional activity of chickpea protein. Reduce allergenicity of plant proteins by degrading allergens and antinutritional compounds.	Schlegel et al.,[93] Meinlschmidt et al.[94]
other modification techniques			
complexation	proteins interact with other molecules in a number of ways, such as hydrophobic, electrostatic, hydrogen bonding, van der Waals, steric repulsion, and disulfide bridges. This allows for the creation of micro- and nanoparticles with enhanced or new technical and functional stability.	complexation of protein-phenolic enhances antioxidant, antimicrobial, anticancer, antiallergenic, anti-inflammatory properties.	Fan et al.,[95] Hu et al.,[96] Zheng et al.[97]

https://doi.org/10.1021/acsfoodscitech.5c00416
ACS Food Sci. Technol. 2025, 5, 2877−2891

Table 4. Functionality of Non-Protein Substances Utilized in the Production of Protein-based Meat Analogues (Sha et al.,[45] Imran et al.,[19])

non protein Sources	constituents	functionality
lipids (fat and oils)	sunflower oil, coconut oil, soybean oil, canola oil, sesame oil, cocoa butter, safflower oil, avocado oil. fat substitutes: carbohydrates (resistant starches, amorphous cellulose fibers, modified starches), and modified lipids.	increase mouthfeel, nutrition (n-3 fatty acid-rich oils), flavor, and texture (saturated fats). impart the sensory qualities of meat, such as juiciness, tenderness, and flavor release
binding agents	carrageenan, xanthan gum, calcium alginate, and transglutaminase, cellulose, methylcellulose, hydroxypropyl methylcellulose, alginates	protein particle binding, moisture retention, shelf stability, volume expansion, and enhanced product smoothness and consistency
colorants	canthaxanthin, lycopene, leghemoglobin, beet juice extract, pomegranate fruit powder, caramel color, malt, cumin, and annatto	to mimic the color of meat after cooking, or to add brightness and produce red and other colors
thickening agents	reducing sugars (such as galactose, mannose, arabinose, xylose, lactose, maltose, and dextrose) lecithin, inulin, maltodextrin, wheat flour, oat fiber, fermented rice flour, butternut squash puree, carrot puree, sweet potato puree, apple fiber, potato starch, potato dextrin, wheat starch, tapioca starch, modified corn starch, tapioca starch, guar gum, gum Arabic, etc.	to emulsify oils, decrease syneresis, enhance rheology, texture, and consistency, and adhere water and immobilization of fat
flavouring agents	soy sauce, cane sugar, evaporated cane syrup, molasses, dextrose, lactose, mannitol, vinegar, succinic acid, lactic acid, lemon juice, onion powder, celery, walnuts, oats, sodium chloride, potassium chloride, sodium inosinate, and guanylate (nucleotides),	to enhance the overall smell and taste of the product and replicate the flavor of processed meat.
minerals	compounds include sodium chloride, potassium chloride, calcium chloride, calcium acetate, ferrous sulfate (iron), calcium phosphate, sodium phosphate, sodium pyrophosphate, tripolyphosphate, and hexametaphosphate, and magnesium carbonate.	to enhance nutritional value and retain water.
vitamins	thiamine (vitamin B1), riboflavin (vitamin B2), niacinamide (vitamin B3), pyridoxine hydrochloride (vitamin B6), folic acid (vitamin B9), and cobalamin (vitamin B12)	to enhance vitamins and overcome inadequacies.
antioxidants and antimicrobials	various herbs, spices, and their extracts, as well as mixed tocopherols. polyphosphates, lactic acid, and other spice extracts.	to minimize oxidative off-flavor and discolouration, and to extend product shelf life.

linoleic acids. Oil or lipids serve as emulsifiers or lubricants for the protein phase, influencing melt rheology, system parameters, and associated product properties.[107] The presence of fat promotes laminar flow of the protein phase, resulting in the creation of linkages that enhance fibrosity in the material. Lipids serve as lubricant during thermomechanical processing, influencing melt viscosity, alignment behavior, and resulting mouthfeel. Small levels of plant-based oils (such as sunflower or coconut oil) are distributed along the protein matrix during shear processing, increasing laminar flow and lowering frictional resistance.[108] This can help to align protein chains and promote the growth of fibrous layers. However, high lipid content can impede protein−protein interactions, resulting in weaker structure development. The final texture is also influenced by the lipid type and melting point—solid fats produce a harder bite, whereas liquid oils improve juiciness and retain moisture.[15]

According to previous reports, adding oil improves the textural qualities of meat analogs while reducing the amount of mechanical energy used. Thus, when creating a meat analog, the oil concentration significantly affects the continuous network and degree of structure creation.[109] The balance between unsaturated and saturated fatty acids is critical to recreating the sensory properties of meat. However, PBMA's high saturated fat content of PBMA requires careful consideration to ensure its health. To improve human health, experts aim to reduce the fat content in meat products, as excessive consumption is linked to harmful effects. One alternative is to use a fat replacement made of water and functional substances. Fat alternatives are suggested when developing low-fat plant-based meat products, in which texture, softness, and juiciness need to be improved. Low-fat meat alternatives can be prepared using fat substitutes. Plant proteins such as soy protein isolate, animal proteins such as milk and eggs, carbohydrates such as resistant starches, amorphous cellulose fibers, modified starches, and modified lipids are examples of fat alternatives.

3.5. Role of Other Ingredients in PBMA. Additives improve the structural qualities of meat analogs, including their fibrousness, strength, and springiness. The formulation of PBMA includes a variety of plant- or animal-based components that are utilized as gelling agents, emulsifiers, thickeners, stabilizers, and binding agents. These ingredients can bind to water and provide meat substitutes for adhesion. However, there has been an increase in the ingredients that can impact customer acceptability and environmental sustainability.[110]

Binding agents improve product consistency and smoothness while retaining the fat and moisture content. Binding agents not only bind fats and water but also improve the appearance and texture of the contents.[19] Hydrocolloids that bind materials and reduce oil absorption include zein proteins, alginates, methylcellulose, hydroxypropyl methylcellulose, and long-fiber cellulose.[103] Methylcellulose is a common component of many plant-based meat substitutes. Methylcellulose is a crucial component of PBMA because of its additional qualities, which include reduced cooking loss, binding ability, and reversible heat gelation.[111] In the development of protein-based meat substitutes, gums such as locust bean gum, xanthan gum, methylcellulose, carrageenan, and calcium alginate have also been used to increase the water-holding capacity of proteins.

Color is one of the most crucial elements. The red color of raw fresh meat typically turns brown when cooked; therefore,

https://doi.org/10.1021/acsfoodscitech.5c00416
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developing plant-based meat that can replicate and resemble traditional meat can be difficult.[78] Because soy and gluten, two of the most popular plant-based proteins, are naturally yellow or beige, it is necessary to make them more vibrant when coloring agents are used.[112] Coloring agents can be added with semistructured plant-based materials during structuring or with proteins prior to the structuring treatment. Despite their development, natural pigments from renewable sources cannot be used directly because of their limitations, including chemical degradability, instability at high temperatures and pressures, and loss of functionality during storage. In addition to reducing sugars (such as dextrose, maltose, lactose, xylose, galactose, mannose, and arabinose), caramel (annatto or malt; carotene, cumin, and turmin) and beet root extracts are used to mimic the color of cooked or roasted meat.[113,114] Protein amine groups can combine with reducing sugars to produce the Maillard reaction, which adds desirable flavor and color.[115] Hydrated alginate and maltodextrin are coloring additives that prevent color migration during manufacturing. Leghemoglobin, lycopene, annatto, and beet juice extracts can also simulate the color of red meat, whereas titanium dioxide can simulate the color of chicken flesh.[116] Soy leghemoglobin is a color additive approved by the Food and Drug Administration in 2019 (FDA). Biotechnology has successfully produced leghemoglobin, a heme pigment derived from soybean plants. The FDA allows a maximum application of 0.8% by the product weight of this color additive in ground meat analogs. Soy leghemoglobin can replicate the ″bloody″ appearance of animal haem proteins (hemoglobin and myoglobin). Thermal stability and pH sensitivity are critical for production of plant-based meat products. The deterioration of thermally unstable compounds may result in an undesirable color appearance.[113] Plant-based meat which is usually fortified with polyphenol and ascorbic acid-rich liquids, such as apple or citrus fruit extracts. Furthermore, these juices can act as preservatives and antibacterial agents.[106]

Flavor is also a crucial sensory component in the development of plant-based meat analogs. Raw meat lacks aroma and only tastes blood, metal, and salt, whereas cooked and roasted meat develops complex flavor compounds through the Maillard reaction, fatty acid oxidation, thermal degradation of thimines, and other processes.[117,118] Plant-based meat substitutes mostly consist of soy protein and wheat gluten, which lack the intermediate molecules necessary to produce meat-like flavors.[119] Consequently, meat-like flavorings are added to meat substitutes to mimic the flavors and aromas of real meat.[120] To mimic the flavors of processed meat, PBMA is flavored with a variety of spices and herbs, including those used in the meat-processing industry. The compounds used to enhance the taste of plant-based meat substitutes can be classified as follows: (i) natural herbs and spices that stop lipid oxidation; (ii) Maillard reaction precursors that produce meat-like flavors by reducing sugars, amino acids, and thiamine; (iii) hydrolyzed vegetable proteins that enhance meat-like flavor; (iv) yeast extract that adds a roasted, meat-like scent; and (v) vegetable oils that contribute to the mouth feel of plant-based meat products.[121] The most commonly used spice mixtures include dried onions, dried garlic, curry powder, black pepper, chilli, paprika, and ginger. The most commonly used aromatic plants in plant-based meat production are parsley, dill, basil, oregano, sage, coriander, rosemary, marjoram, tarragon, bay, thyme, and mint.[122] These herbs contain bioactive molecules that can positively impact human health. The addition of herbs and spices can also mask any off-flavors, and organic acids that may be present in these herbs and spices can extend their shelf life.[123−125]

4. CHALLENGES AND FUTURE PROSPECTS OF SHEAR CELL TECHNOLOGY

Shear cell technology is a novel approach for developing PBMAs that use flow-induced material structuring to build various product forms. Its key advantage is its ability to change the shear conditions (rate and temperature) to achieve the desired results. Additionally, studies have shown that the mechanical energy input required for the structuring process may be far less than that required for forced assembly methods, such as extrusion. Recent studies using shear cell technology have demonstrated that plant-based proteins can be used to create a fibrous texture similar to that of meat. However, because the distance between the cones gradually increases throughout the radius, the shear rate in the Shear Cell varies over the volume of the protein sample. Most significantly, the scalability of this configuration restricts its use in laboratory-scale experimentation. To further clarify the advantages and limitations of shear cell technology, a comparative overview with other established structuring methods such as high-moisture extrusion and freeze structuring is provided in Table 5. The comparison includes key factors like energy consumption, processing conditions, texture quality, and scalability. Shear cell technology is promising, but it has a number of technical issues that need to be resolved before it can be used extensively in industry. The conventional cone−cone shear cell design's nonuniform shear distribution caused by geometric gradients is a significant scalability barrier that prevents consistent structuring over bigger batches.[110] Additionally, in contrast to continuous techniques like high-moisture extrusion, batch processing limits throughput and efficiency. Commercial production scaling is further complicated by the absence of automation and integration with downstream operations. Recent studies have concentrated on sophisticated designs like Couette cells, which provide more consistent shear stress and greater possibility for scaled, continuous operation.[52] However, in order to establish shear cell technology as a competitive alternative in the production of plant-based meat, these obstacles must be addressed. The newly developed Couette cell is a novel technique for

Table 5. Comparative Analysis of Shear Cell Technology with Other Plant-Based Meat Structuring Methods Based on Processing and Performance Parameters (Jang et al.,[3] Cornet et al.,[15] Angonese et al.[24])

parameter	shear cell technology	high-moisture extrusion (HME)	freeze structuring
shear force	moderate	high	non
temperature (°C)	90−140	130−160	−10 to −40
energy consumption	low	high	low to moderate
process type	batch	continuous	batch
residence time	<20 min	2−5 min	17−24 h
product texture	fibrous, layered	dense fibrous	flaky, less dense
scalability	currently limited	industrial scale	research/lab scale
equipment cost	moderate	high	high

https://doi.org/10.1021/acsfoodscitech.5c00416
ACS Food Sci. Technol. 2025, 5, 2877−2891

producing fibrous meat analogs. Studies demonstrate that, under practical circumstances (temperature: 90−110 °C, process time: 5−25 min, rotation rate: 5−50 rpm), SPI-gluten mixtures may be shaped using a Couette Cell into fibrous, anisotropic, and multilayer structures. Fibrous structures were regularly observed at processing temperatures above 90 °C and below 100 °C. The Couette cell produced fibrous and multilayer structures that could be seen with the naked eye. Under mild conditions, the Couette cell uses simple shear and heat to create anisotropic fibers. Additionally, it enables scalable and continuous processing and can possibly operate continuously. Scaling up in the radial direction is more valuable, resulting in increased product thickness. Hence, based on earlier research and experiments, a new up-scaled Couette cell was built. It treats approximately 7 kg every batch, which is more than 45 times the lab-scaled cell volume. There is considerable potential for expanding the industrial production of meat alternatives using shear cell technology. This upscaling is viewed as the final step before the industrial manufacturing of fibrous meat replacers presents a viable business opportunity. When implemented in an industrial setting, automation and process integration can further enhance the upscaled Couette Cell process. Feeding, cleaning, lid opening and closing, and process control can all be automated, and the entire process can be integrated with additional steps, such as product handling, protein mixture preparation, packaging, and freezing. Although the Couette cell design tackles some of these concerns by allowing for more uniform shear and the possibility of continuous processing, it is still in the developmental or pilot stage. Other obstacles include limited ingredient compatibility, particularly for gluten-free or allergen-free formulations, as well as the necessity for careful thermo mechanical parameter control to avoid structural collapse. Hence, future efforts should concentrate on engineering solutions to increase shear uniformity, the move to continuous processing systems, and increasing ingredient flexibility. The use of hybrid procedures, such as combining shear cell technology with nonthermal treatments like as high-pressure processing or sonication, may improve structural integrity and nutritional value. Addressing these technical limitations is critical for turning laboratory successes into industrial practicality, hence facilitating the widespread commercialization of plant-based meat alternatives.

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Notes

The authors declare no competing financial interest.

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https://doi.org/10.1021/acsfoodscitech.5c00416
ACS Food Sci. Technol. 2025, 5, 2877−2891