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ABSTRACT

The development of plant-based meat analogs (PBMAs) has emerged as a sustainable and ethical alternative to traditional animal meat. Achieving the fibrous texture and sensory qualities of animal meat presents significant challenges due to the structural differences between plant and animal proteins. Advanced computational techniques, particularly finite element analysis (FEA), offer promising solutions to these challenges by simulating and optimizing the mechanics, thermodynamics, and mass transfer behaviors of PBMA during processing. This review explores the role of FEA in addressing critical aspects of PBMA development, including texture replication, stability during storage, texture after heating, and variability in plant protein sources. Key processing techniques, such as high-moisture extrusion, shear cell technology, and extrusion 3D printing, are analyzed for their potential to create fibrous, meat-like textures. The review also highlights the integration of FEA methods like advanced rheological models and coupled multi-physics simulations to predict and enhance texture formation, juiciness, and thermal stability. Future perspectives emphasize interdisciplinary collaboration among food sciences, solid and fluid mechanics, and computational physics to refine predictive models, improve efficiency, and accelerate PBMA innovation. This review highlights that leveraging computational tools can provide a pathway for the consistent and scalable production of high-quality PBMAs that align with consumer expectations and sustainability goals.

I. INTRODUCTION

The rising consumer demand for sustainable food options, combined with concerns over the environmental impact of livestock production and animal welfare, has led to increased interest in plant-based meat analogs (PBMAs). These products are designed to replicate the sensory experience of traditional meat while providing a more ethical and environmentally friendly alternative.[1] In 2024, the global PBMA market is valued at an estimated $9.94 billion, with a projected compound annual growth rate (CAGR) of 16.9% from 2023 to 2024. This market is anticipated to reach $17.23 billion by 2028.[2]

Despite the long-standing presence of traditional meat alternatives like tofu, tempeh, and seitan, modern PBMAs are being developed to more closely mimic meat's sensory attributes, nutritional profile, and culinary functionality, making them more appealing to omnivores and flexitarians.[3–5] Modern PBMAs are primarily made up of plant proteins, such as soy, pea, and wheat gluten, which typically account for 40% to 80% of the product by dry weight.[6–8] However, plant proteins are predominantly globular, while meat proteins form long, fibrous chains that align to create muscle fibers, making it challenging to replicate the fibrous, meat-like texture.[9] Although advanced processing techniques such as high-moisture extrusion (HME), shear cell technology, and extrusion 3D (three-dimensional) printing have shown promise in aligning plant proteins, replicating the hierarchical organization of muscle fibers, from microscopic actin and myosin filaments to macroscopic bundles, remains a considerable challenge.[4,10,11] Unlike animal proteins, which can self-assemble into well-organized fibrous structures, plant proteins lack this capability, requiring precise control over processing conditions such as temperature, shear force, and pressure to induce the necessary structural changes.[12,13] Additionally, variability in plant protein sources makes it difficult to consistently reproduce the desired texture.[14]

Finite element analysis (FEA) presents a promising approach to address these challenges by offering a computational method to understand and optimize the processing of PBMAs. FEA has been successfully applied in various food-related contexts, such as predicting heat and mass transfer during baking, modeling the deformation of starch-gluten dough during extrusion, and optimizing freeze-drying processes for fruits.[15–17] These applications demonstrate the versatility of FEA in providing insights into the mechanical and thermodynamical behaviors of food materials under different processing conditions. In the production of PBMAs, FEA can potentially help optimize protein alignment and structural stability to form cohesive and fibrous networks that mimic animal muscle by simulating the processing conditions. Additionally, FEA can simulate heat- and moisture-induced changes, ensuring that PBMAs maintain their desired texture and quality throughout heating and storage. Furthermore, FEA is expected to achieve consistent texture and manage the variability of plant protein sources by predicting the mechanical responses and deformation behaviors under various processing conditions.

This review aims to investigate the potential of using FEA to address key technological challenges in developing the texture of PBMAs. Currently, the combined use of computational modeling and experimental validation in PBMA development remains underexplored, limiting the optimization of processing techniques and the consistent replication of meat-like texture in PBMAs. By focusing on the computational modeling of mechanical and thermal behaviors, this review provides valuable insights to guide the development of consistent, high-quality PBMAs with enhanced texture. Ultimately, these efforts contribute to food soft matter physics and PBMA development, aligning with environmental goals and addressing the rising demand for ethical food choices. This review mainly includes scientific papers published within the past five years.

II. REPLICATING THE TEXTURE OF ANIMAL MEAT

Animal meat has a complex texture mainly composed of muscle tissues, connective tissues, and fat [Fig. 1(a)],[12] which contributes to its mechanical properties and heating behaviors.[12,18] Understanding the texture of animal meat is important for developing PBMAs that replicate these qualities.

A. Texture of animal meat

Muscle tissue, which constitutes 30%–65% of an animal's total body weight, depending on species and other factors, is made up of long, multinucleated cells known as muscle fibers or myofibers.[12] In large muscles, some fibers can reach lengths of up to 30 cm.[19] As shown in Fig. 1(b), muscle fibers are hierarchically organized into bundles, or fascicles, which combine to form entire muscles. Each fiber contains repeating units of sarcomeres, the basic contractile structures composed of actin and myosin.[12] The parallel arrangement of myofibrils within the fibers gives meat its fibrous texture and creates the

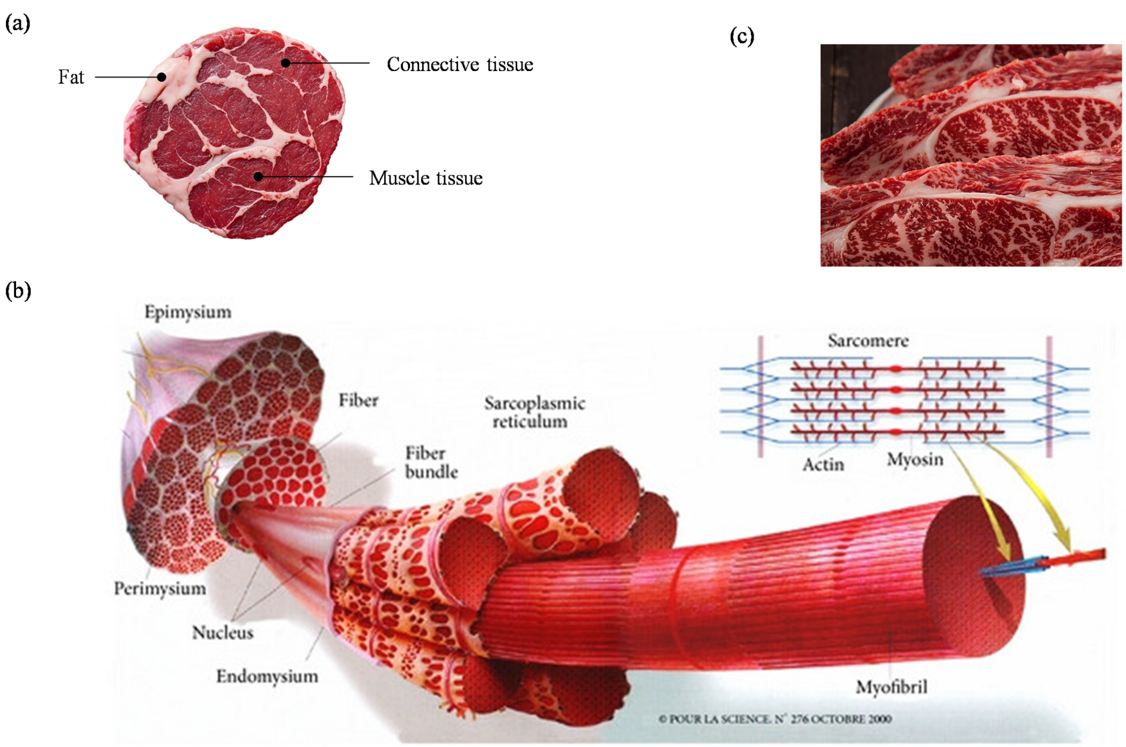

FIG. 1. Components and organization of animal meat. (a) Main components of animal meat; (b) general organization of animal muscle;[22] (c) marbling in animal meat.

"grain" seen in meat cuts. This fibrous nature provides mechanical integrity, and during mastication, the alignment of muscle fibers affects the perception of toughness or tenderness.[20] Long, unbroken fibers tend to make meat tougher, while cuts with shorter or disrupted fibers, often achieved through tenderizing, are perceived as more tender.[21] When meat is cooked, the fibrous muscle structure undergoes several changes that affect its texture. Heat denatures the proteins within the muscle fibers, causing actin and myosin to shrink, which makes the meat firmer and leads to moisture loss.

In addition to muscle fibers, connective tissues, particularly collagen, play an important role in the structural integrity and texture of animal meat.[12] Collagen surrounds individual muscle fibers, fiber bundles (fascicles), and entire muscles, forming a supportive framework. The distribution and type of collagen vary across muscle types and animal species, influencing textural differences between cuts, such as the tender tenderloin vs the tougher, collagen-rich shank.[23] In younger animals or tender cuts, collagen is more soluble and breaks down into gelatin during heating, enhancing tenderness. In tougher cuts or older animals, collagen is more fibrous and does not break down as easily, leading to a chewier or tougher texture. In addition, collagen behaves differently depending on heating temperature, undergoing distinct structural changes that affect the texture of meat. At lower temperatures, collagen remains intact, while at higher temperatures, it breaks down into gelatin, softening tougher cuts and creating a melt-in-the-mouth texture. However, the extent of collagen breakdown depends on both heating time and method; rapid heating may prevent full gelatinization, leading to tougher textures in collagen-rich cuts.[24]

Fat is another important component found within animal meat, especially in the form of intramuscular fat, or "marbling" [Fig. 1(c)]. Marbling refers to small amounts of fat dispersed between muscle fibers, playing a key role in enhancing the juiciness and flavor of meat.[12] During heating, fat melts and lubricates the muscle fibers, improving tenderness and mouthfeel. Cuts of meat with higher marbling are generally more desirable because they retain more moisture, resulting in softer, more succulent meat.[25]

B. Mechanism of PBMA texture creation

As mentioned in Sec. I, plant proteins are the primary ingredients of PBMAs, typically accounting for 40% to 80% of the product by dry weight.[6–8] While certain plant proteins, such as wheat gluten (seitan), naturally form fibers when hydrated and kneaded due to the alignment of gluten proteins into a fibrous network, most plant proteins are typically globular, exhibiting a compact, folded structure.[26] To create PBMA, plant proteins are unfolded and restructured into aligned, elongated fibers using processing techniques such as extrusion.[11] Soy protein, pea protein, and wheat gluten are commonly used in PBMA due to their excellent gelation, emulsification, and water-binding properties.[13] These proteins can form strong, cohesive networks when subjected to heat, pressure, and shear forces, which are essential for creating fibrous, meat-like textures.[27]

The process of protein structuring for PBMAs involves several steps, including protein unfolding, degradation, and subsequent aggregation through covalent and non-covalent bonds. This process results in the formation of fibers (fibrils) with diameters ranging from nanometers to micrometers.[28] Protein denaturation is a critical step in fibrous structure formation, involving the disruption of a protein's native structure. This can be induced by heat, mechanical forces, or changes in pH, all of which disrupt the protein's secondary and tertiary structures. As a result, the compact globular proteins unfold into linear, flexible chains.[29] Once the proteins are denatured and unfolded, the next step is alignment, typically achieved through the application of heat, pressure, and shear forces.[30] Techniques such as HME, shear cell technology, and extrusion 3D-printing are commonly used for this purpose (further discussed in Sec. II C). In addition to alignment, protein cross-linking plays a critical role in stabilizing the fibrous structure. Cross-linking occurs when proteins form covalent or non-covalent bonds with each other, thereby stabilizing the fibrous network.[31] Gelation is another significant mechanism in fibrous structure formation. Proteins aggregate into three-dimensional networks that trap water, forming gels. In PBMAs, gelation helps create a cohesive matrix that holds the fibrous structure together.[32] Proteins such as soy and pea are particularly adept at forming gels under the appropriate conditions, contributing to the firm, fibrous texture of meat analogs.[4] The final step is cooling and solidification. As the extruded or sheared product cools, the protein chains stabilize in their new fibrous arrangement. The cooling process helps lock the fibrous structure in place, resulting in a product with a firm, meat-like texture. The rate and method of cooling can significantly influence the final texture; rapid cooling tends to produce a firmer texture, whereas slower cooling can result in a softer, more tender product.[33] Solidification is essential for maintaining the structural integrity of the PBMA during subsequent processing, heating, or consumption.

Water plays a critical role in creating the texture of PBMAs by acting as both a plasticizer and an agent of molecular mobility. During extrusion or other thermal processes, adequate hydration ensures proper protein unfolding and the formation of cohesive fibrous strands, while insufficient moisture can result in brittle textures.[26] Conversely, excessive water may inhibit the development of a strong fibrous network, yielding a mushy product.[34] During cooling, water also affects the texture by influencing the rate of protein solidification and stabilization. The water content and distribution within the protein matrix are critical in determining the mechanical properties of the final product, which contribute to key sensory attributes such as juiciness, chewiness, and mouthfeel, which are the factors crucial to the consumer experience of PBMAs.[35]

C. Processing techniques for PBMA texture development

The PBMA production process begins with the selection of plant-based ingredients, primarily proteins, along with lipids and carbohydrates as needed.[36] These ingredients may undergo functionalization through physical, chemical, or enzymatic methods to enhance properties such as water-holding capacity, gelation, and emulsification.[29] A pivotal stage in the process is texture development, which utilizes advanced techniques to create fibrous, muscle-like structures that mimic meat. During formulation, protein- or polysaccharide-based binders and texturizing agents are incorporated to ensure structural stability and integrity.[4] Flavor and color are refined through advanced flavor chemistry techniques, including Maillard reactions and enzymatic modifications, to achieve umami and roasted meat-like notes.[37] Natural pigments and plant-derived heme proteins are often used to enhance the visual authenticity of the product.[5,38] Nutritional fortification with essential nutrients such as iron, vitamin B12, and omega-3 fatty acids ensures that PBMAs match or exceed the nutritional profile of traditional meat.[4] Thermal treatment is typically applied to ensure food safety and develop desirable sensory properties. The final assembly of PBMAs, shaping them into products such as patties or sausages, is tailored to improve marketability.[13] Finally, packaging and preservation techniques, including modified atmosphere packaging (MAP), are employed to maintain product quality and extend shelf life.[39]

This Section discusses the key mechanical processing techniques used to develop the texture of PBMA. Although some biotechnological methods, such as enzyme treatments (e.g., using transglutaminase and laccase) and fermentation processes involving mycelium-based structures are also used, they are not covered in this review.

1. High-moisture extrusion (HME)

HME is one of the most widely used techniques in PBMA production. This method relies on a combination of shear force, heat, and pressure to denature and align plant proteins, transforming them into structured, fibrous networks that closely mimic the texture and functionality of meat.[11]

Plant protein ingredients are typically mixed with other components to create a high-moisture mixture (typically around 60%–80%).[11] As shown in Fig. 2, during HME, this mixture is fed into an extruder, a cylindrical device equipped with rotating screws. The production of PBMAs typically uses co-rotating twin-screw extruders.[40] These screws generate mechanical shear forces that disrupt non-covalent interactions and hydrogen bonds, destabilizing the native structure of plant proteins. This leads to protein denaturation, chain unfolding, and alignment along the flow direction.[41,42] Shear also imparts viscoelastic properties to the protein melt, facilitating the development of a cohesive and fibrous texture.[43] Additionally, shear force fosters phase separation between proteins and other components, such as polysaccharides, enhancing the layered structure of the final product.[4,31] Proper control of shear is important, as excessive shear force can lead to overly dense or rubbery textures, whereas insufficient shear force may yield a product lacking structure.[44]

Heat is applied within the extruder, further promoting protein denaturation and aiding in the aggregation of protein molecules into fibrous structures.[11] Heat also plays an important role in activating the Maillard reaction (when reducing sugars are present), enhancing the flavor, color, and aroma of the final product.[45] In addition, heat maintains the protein mixture above its glass transition temperature (Tg), enabling flow and alignment under shear forces.[46] Furthermore, water acts as a plasticizer under heat, lowering the glass transition temperature of the protein matrix and increasing protein mobility and flexibility.[11,44] However, overexposure to heat potentially causes off-flavors and reduces nutritional quality.[47]

In HME, the rotating screws compress the material, increasing pressure as it moves toward the die. At the die exit, the mixture experiences maximum pressure.[11] The compressive forces within the extruder increase the frequency of molecular collisions, encouraging interactions such as covalent disulfide bonds and hydrophobic interactions. This compression also stabilizes protein conformations conducive to fibrous structuring.[35] In addition, pressure enhances water retention, preserving the pliability of the protein matrix and minimizing excessive evaporation during processing. Furthermore, pressure elevates the boiling point of water, enabling higher processing temperatures without phase transitions. The pressure drop at the die exit is particularly significant, causing rapid cooling and solidification of the aligned protein structure and preventing reversion to the globular protein form.[11]

The success of the HME process depends on balancing shear force, heat, and pressure to optimize protein structuring, moisture retention, and flavor development. The resulting product exhibits a meat-like fibrous texture that is comparable to cooked muscle tissue, making it suitable for products such as plant-based chicken or beef analogs.[11,48]

However, HME can significantly alter the functionality of plant proteins and other ingredients, which impacts texture, flavor, and nutritional quality. High temperatures and shear forces during extrusion can cause protein denaturation and aggregation, leading to a potential loss of heat-sensitive nutrients such as certain amino acids and vitamins.[37,49] Additionally, processing conditions need to be controlled to prevent the development of unwanted flavors, as some plant proteins, especially soy, are prone to producing bitter or beany off-flavors when exposed to heat.[50] These off-flavors are typically the result of lipid oxidation or the release of volatile compounds, and they can negatively affect the sensory qualities of the final product.[47,50]

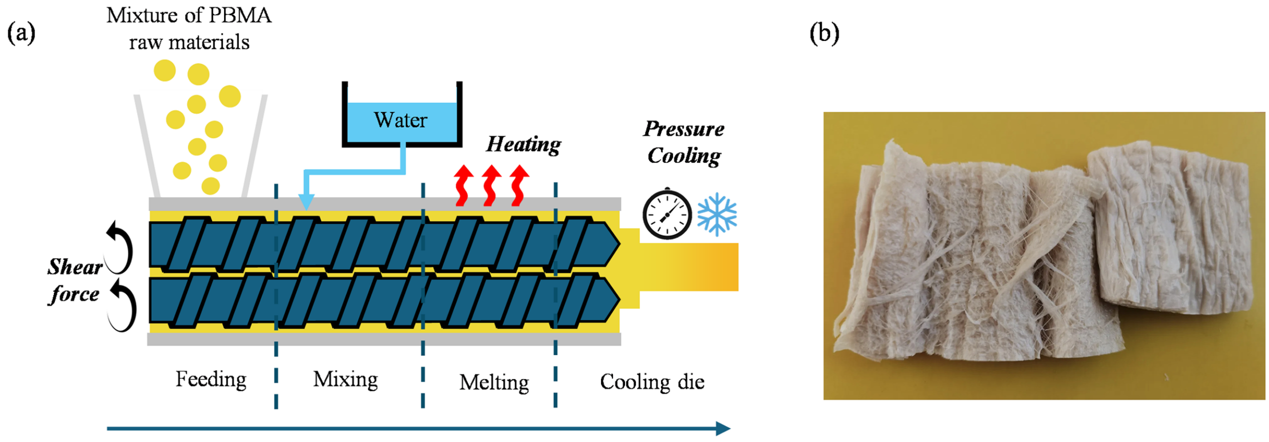

FIG. 2. HME: (a) schematic of the process and (b) PBMA prototype produced by HME.

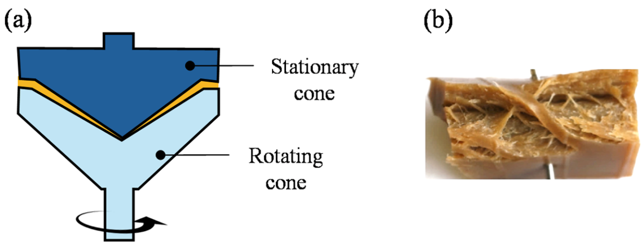

FIG. 3. Shear cell technology: (a) schematic of the process and (b) PBMA prototype produced by shear cell technology.[52]

2. Shear cell technology

Shear cell technology is another promising technique that applies controlled, continuous, and uniform shear forces to plant protein mixtures.

In shear cell technology, plant proteins are mixed with water to form a dough-like material, which is then placed in a specialized device known as a shear cell. As shown in Fig. 3, this device consists of concentric cylinders or plates, where one part rotates while the other remains stationary, generating shear forces as the protein mixture is pressed between the rotating and stationary surfaces.[51]

Unlike HME, which uses both heat and high pressure, shear cell technology operates at lower temperatures with gentler mechanical forces, making it more energy efficient. The lower processing temperature helps preserve the native structure of proteins, enhancing the texture and potentially retaining more functional properties in the final product. During processing, the protein molecules unfold and align in the direction of the applied forces, forming a fibrous structure similar to the parallel arrangement of muscle fibers in meat.[36] This precise control over the alignment process allows for the formation of highly structured fibers that closely mimic the texture of animal meat, with minimal thermal degradation, making it suitable for simulating whole cuts meat products like chicken or beef, without relying heavily on binding agents, resulting in a more natural texture.[4] However, in some formulations, small amounts of additives may still be required to ensure product stability.[53]

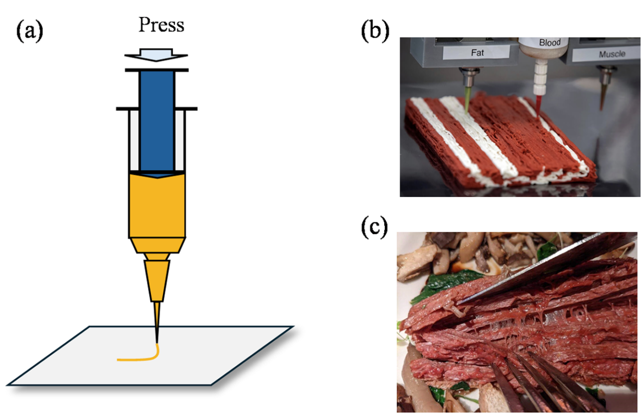

FIG. 4. Extrusion 3D printing: (a) schematic of the process; (b) industrial application of extrusion 3D printing to produce PMBAs;[55] and (c) cooked PBMA product produced by extrusion 3D printing.[55]

Shear cell technology excels at processing high-moisture content mixtures, which contributes to the juiciness and desirable mouthfeel of the final product.[4] However, shear cell technology currently performs best with low-fat-content plant-based meat analogs with fat content below 10%,[54] which necessitates further research to broaden its application to products with higher fat content.

3. Extrusion 3D printing

Extrusion 3D printing is an emerging technology in the field of PBMA production, offering significant control over product structure and design. This technique involves the layer-by-layer deposition of plant-based protein materials through a 3D printer's extrusion nozzle. In extrusion 3D printing, a mixture of plant proteins, water, and other structuring agents, such as hydrocolloids or fats, is loaded into the printer. As shown in Fig. 4, the printer extrudes the protein mixture through a nozzle in a controlled manner. As the material is extruded, the printer lays down successive layers of protein, aligning and forming fibrous structures according to the design programmed into the printer.[56]

A key mechanism in 3D printing is the ability to control the orientation and thickness of each layer by adjusting the deposition pattern, nozzle movement, and extrusion speed, allowing the printer to simulate the natural anisotropic alignment of muscle fibers in meat.[57] Material properties, including viscosity and gelling ability, play a critical role in ensuring that the layers bond together and form a cohesive fibrous network.[58]

The inclusion of fats and other structuring agents, such as hydrocolloids and starches, enables the creation of marbling effects that mimic the fat distribution found in animal meat.[56] The technology also allows for the precise incorporation of additional ingredients, such as flavorings, oils, or micronutrients, at specific locations within the product, enhancing the sensory attributes and nutritional profile of the PBMA.[4] As each layer is printed, the material can be cooled to retain a gel structure or heated to enhance structural integrity, depending on the desired texture. By precisely controlling the layering process, extrusion 3D printing enables the creation of complex, fibrous textures that replicate whole-cut meats, such as steaks or chicken breasts.[59]

However, the bond strength between layers in 3D-printed PBMAs may be weaker compared to other methods, especially when lower extrusion temperatures are used, which limits inter-layer cohesion.[60] This reduced bond strength can compromise the structural integrity, making products more prone to crumbling during heating or consumption.[61] Additionally, the process often requires low-fat content in the mixture, as high-fat levels can reduce cohesion between layers and interfere with the alignment of fibrous structures, limiting the replication of marbling found in animal meat.[56] Production speed is also a challenge; the layer-by-layer approach of 3D printing is slower than traditional extrusion, as each layer must be deposited sequentially, making it less efficient for large-scale production and increasing costs for manufacturers.[62] Furthermore, the mechanical strength of 3D-printed PBMAs may be inferior to products created by HME or shear cell technology, as the inter-layer bonds may not be as robust, which can significantly affect key textural qualities like chewiness.[63,64]

III. TECHNOLOGICAL CHALLENGES

Despite notable advancements, PBMAs continue to encounter significant challenges across technological, nutritional, sensory, economic, and environmental domains. This paper focuses on four critical technological challenges: texture creation, stability during storage, changes after heating, and variability in plant proteins and target products.

A. Texture creation

Replicating the texture of animal meat remains a fundamental challenge in PBMA development.[11] The complexity of animal meat lies in its hierarchical, fibrous structure, the retention of water and fats, and the unique viscoelastic properties of muscle proteins, all of which contribute to the overall texture and eating experience. The layered structure provides the characteristic bite and chewiness, while the ability to retain water and fats ensures juiciness, which together define the sensory quality of meat (Sec. II A). Current technologies, such as HME and shear cell processing, often fall short in replicating the intricate details of muscle tissue. Real muscle tissue exhibits a hierarchical complexity, combining both ordered (e.g., sarcomeres) and disordered (e.g., extracellular matrix) structural phases, which allows for intricate physicochemical interactions between muscle fibers, fats, and water.[65] Recreating this dynamic interplay is challenging with plant-based proteins in their unmodified natural forms, as they typically lack the self-assembly mechanisms and structural adaptability characteristic of animal proteins.[66]

The intrinsic heterogeneity of muscle tissue, including its ability to retain water and fats and to provide resistance during chewing, poses significant challenges for PBMA development.[10] Plant-based products typically have a higher dry matter content than meat, which affects juiciness.[67] In addition, the use of additives such as pectin can negatively impact mouthfeel and moisture release, leading to inconsistent textural outcomes.[68] Achieving the elasticity and tensile strength of animal muscle and animal fascia tissues also presents challenges, as plant proteins lack the phase behavior and viscoelastic properties that characterize animal proteins.[69,70]

To address these challenges, optimizing processing conditions, such as shear forces, pressure, and temperature, is essential. Moreover, the use of hybrid protein blends offers an opportunity to leverage the complementary functional properties of different plant proteins. For example, combining soy protein isolate with wheat gluten (SPI-WG) is advantageous due to its enhanced viscoelasticity and robust fibrous structure, closely mimicking the qualities of animal meat. Wheat gluten contributes significantly by promoting disulfide bonding, which supports the formation of a cohesive gel network that imparts chewiness, elasticity, and effective water retention, essential for replicating the texture and juiciness of meat.[71]

B. Texture stability during storage

Plant proteins, carbohydrates, and fats, as the main ingredients in PBMA, undergo physical and chemical changes during storage. Unlike animal meat, where proteins and fats are naturally structured to retain stability, plant-based analogs require carefully engineered interactions between ingredients to maintain texture.[11,13] As the primary ingredient of PBMA, plant protein can undergo denaturation or aggregation over time, leading to texture changes, such as hardening or crumbling.[29] Moreover, plant proteins tend to degrade faster than animal proteins when exposed to environmental factors, often requiring stabilizers or binding agents to maintain structural stability over time.[30]

The water content of PBMAs varies depending on the product, often ranging from 50% to 70%.[8] During storage, moisture within the PBMA product may migrate from high-moisture components (e.g., plant proteins) to lower-moisture regions, resulting in uneven moisture distribution and altered water activity. These changes can affect mechanical properties and, consequently, the texture of PBMA. Moisture loss may cause proteins and fibers to lose hydration, resulting in a firmer or sometimes overly chewy texture that is less appealing. Conversely, excess moisture may lead to a soggy or gelatinous consistency. Uneven moisture distribution also affects flavor release and stability. Drying out can intensify certain flavors, making them concentrated or even stale, while excessive moisture may dilute flavors, rendering the product bland. Additionally, temperature fluctuations can exacerbate moisture migration within PBMA.[72] Typically, PBMAs use plant-derived polysaccharides or hydrogels to retain moisture and simulate the juiciness of meat. However, these water retention agents may lose effectiveness over time.[73]

Fat content, ranging from 5% to 20% on a dry basis in PBMAs, enhances juiciness and mouthfeel.[8,74] Factors related to fat that influence the stability of PBMAs primarily include fat crystallization and oxidation. Temperature fluctuations during storage may induce phase transitions in fats (e.g., fat crystallization), thereby impacting the product's mouthfeel and overall quality. Additionally, oxidation may occur, especially during prolonged storage, which can lead to off-flavors and textural degradation, thus compromising the sensory quality and stability of the product.[73,75]

Currently, stabilizers, emulsifiers, antioxidants, and controlled atmosphere packaging are commonly used to maintain PBMAs' integrity during storage. However, the use of additives can affect the clean-label appeal of products. Additionally, even with these measures, prolonged storage can still lead to quality degradation, such as loss of fibrous structure and changes in texture.[76] Research into optimizing storage conditions to minimize moisture migration and phase transitions should be conducted to enhance PBMAs' quality over time. Advances in ingredient encapsulation and the development of natural additives can also help improve the shelf stability of PBMAs.

C. Texture after heating

Developing PBMAs that retain desirable texture and structural integrity post-heating presents a complex challenge due to the fundamentally different thermal behaviors of animal and plant proteins. Animal proteins exhibit unique responses to heat, especially in terms of texture and moisture retention, which are difficult to replicate in plant-based analogs. A primary challenge lies in emulating the transformation in firmness, juiciness, and mouthfeel typical of cooked meat while avoiding common issues in plant-based products, such as dryness, toughness, or structural breakdown.

When heated, animal proteins like myosin and collagen undergo denaturation, which imparts a tender, fibrous texture.[77] In contrast, plant proteins, which are largely globular, lack comparable heat-induced transformations and are prone to uneven denaturation, often leading to excessive firmness due to structural water loss or uneven contraction, or a grainy mouthfeel.[78–80] This challenge is further compounded by differences in moisture retention: during heating, animal muscle fibers release and retain water, while plant proteins generally lack this water-holding capacity, leading to moisture loss and a dry, crumbly texture.[12,81] To mitigate this, the PBMA formulation can include hydrocolloids or binders, such as methylcellulose, which help retain water upon heating.[4] However, achieving the nuanced release and retention of moisture seen in animal proteins remains an area of ongoing development. Some polysaccharides used to enhance moisture retention may also become overly viscous or degrade upon heating, further complicating the preservation of a firm texture.[82]

To ensure the stability of PBMA's texture after heating, it is crucial to address the structural instability caused by the limited thermal expansion and contraction of plant-based ingredients. To address this, heat-stable hydrocolloids like carrageenan and thermally resilient proteins are integrated to maintain texture; however, finding this balance without adversely affecting flavor or mouthfeel remains challenging.[26,53,83] Additionally, strategies such as partial pre-heating and refined heat treatments are employed to improve texture quality after heating.[4,84] However, these methods often fall short of replicating the nuanced texture changes observed in animal meats, with PBMAs sometimes becoming overly soft or rigid. The type of plant protein used further complicates consistency, as the thermal response can vary. This variability can lead to degradation or phase separation upon heating, impacting texture uniformity and appearance.

D. Variability in plant proteins and target products

The inherent variability in plant proteins, combined with the diverse range of target products, poses considerable challenges to the development of consistent, high-quality plant-based meat analogs. Plant proteins exhibit diversity at multiple structural levels, including primary, secondary, and tertiary structures, and vary substantially in functional properties, such as hydration capacity, gelling ability, and emulsification. These differences arise from factors such as plant species, processing methods, and environmental conditions during cultivation.[85] This variability significantly impacts product texture, flavor, and nutritional profile, complicating the production of uniform products that meet consumer expectations for taste and mouthfeel across various plant-based meat analogs, including those replicating beef, chicken, and fish.[86]

Distinct plant sources, such as soy, pea, mung bean, and wheat, possess unique protein compositions, structural characteristics, and functional properties.[86] Such variations mean each type of plant protein has unique viscoelastic and plastic deformation properties, which influence its ability to form fibrous structures consistently, affecting the final texture and mouthfeel.[53,85] Protein composition variability also impacts phase behavior during processing, specifically in terms of the alignment and structuring potential of proteins.[87] Furthermore, the functionality of these proteins can vary depending on their extraction and processing methods.[88] Natural variations in crop composition, influenced by growth conditions, soil quality, and seasonal changes, introduce further challenges to product consistency. Factors such as protein content, hydration capacity, and textural characteristics can fluctuate significantly even within the same protein type, affecting the sensory profile and texture of the final product.[86]

To address these challenges, standardizing processing techniques and incorporating blends of multiple protein sources can help stabilize product characteristics, though achieving consistent quality across batches remains challenging.[89] The targeted product form requires specific mechanical properties. For example, steak analogs need high tensile strength for firmness, whereas chicken breast analogs benefit from moderate extensibility for a softer texture, to achieve desired textural attributes. Crafting these fibrous structures to meet specific product requirements demands precise control over both mechanical forces and thermal conditions, which complicates standardization efforts. Blending proteins such as soy, pea, and wheat allows for optimizing hydration and gelling properties through careful proportion adjustments, mitigating some variability.[71,90] Successfully creating PBMAs that convincingly replicate the sensory qualities of various meats requires sophisticated formulation and engineering approaches.

IV. ROLE OF FEA

To investigate and improve the texture, structure, and sensory properties of PBMAs, the rheological behavior, e.g., motions and deformations due to external loads, is of great industrial interest. This encompasses understanding how the material responds to applied forces, according to its elastic, viscous, and plastic properties across a range of temperatures, strain rates, and time scales. Currently, research in the development of PBMAs has largely relied on experimental methods to investigate these rheological behaviors.[3] While these experimental techniques have proven effective for understanding the conditions that influence product quality, they are often labor- and resource-intensive. As the demand for plant-based meats grows, the computational method has emerged as a promising computational tool that can complement physical experimentation by providing detailed simulations of mechanical, thermal, and flow behavior in PBMA production processes.[91,92] Computational methods have the potential to reduce experimental costs, accelerate development, and offer deeper insights into the detailed physical mechanisms.

Some studies have explored the potential of using computational methods to simulate the behavior of protein materials during food processing. For instance, some studies use computational fluid dynamics (CFD), which is mainly based on the Euler specification and finite volume methods (FVM), to model the mechanical and thermodynamical behaviors of protein materials.[93–95] However, compared with other protein materials like caseins (e.g., cheese) and egg proteins, the mechanical behavior of plant-based protein materials is more similar to that of a solid than a fluid, particularly during extrusion processes. PBMAs exhibit complex solid-like behavior, including viscoelasticity, shear-thinning, and phase transitions under mechanical forces and thermal conditions.[3,37,96,97] These properties are not fully controlled by the Navier–Stokes equations and require a modeling approach capable of capturing not only flow but also deformation, stress, and structural stability, where FEA based on the Lagrangian specification excels. By inputting the rheological properties, e.g., elasticity and viscosity, FEA is expected to predict the rheological behaviors, e.g., deformation and stress distribution.[98]

From the rheological perspective, the target behaviors for PBMAs to mimic meat include elasticity and plasticity, viscoelasticity, and shear thinning behavior.[99–101] Hence, non-linear material models[102,103] and advanced rheological models[104] are important for capturing the viscoelastic and shear-thinning properties of protein materials, allowing for accurate predictions of texture formation and flow behavior. The PMBA is usually a mixture of protein, water, and oil, so its characteristics are sensitive to pressure and temperature.[67] In this context, coupled multi-physics models[105] are critical in extrusion processing as they simulate the interaction of heat, pressure, and moisture, which is vital for producing the fibrous structures characteristic of plant-based meat. In addition, referring to research in food science and other related fields such as biomedical engineering, adaptive mesh

TABLE I. Evaluation of applying different FEA methods to PMBA processing techniques. The applicability is qualified as ●● (probably applicable), ●○ (possibly applicable), and ○○ (nearly inapplicable).

	HME	Shear cell technology	Extrusion-based 3D printing
Non-linear material models	●●	●●	●●
Advanced rheological models	●●	●●	●●
Coupled multi-physics models	●●	●●	●●
AMR	●●	●○	●●
Hybrid approaches combined with FVM, SPH, or LBM	●●	●○	●●

refinement (AMR),[106] and hybrid approaches with methods like FVM,[107] smoothed particle hydrodynamics (SPH),[108,109] or lattice Boltzmann method (LBM)[110,111] offer further improvements in efficiency and detail.

Table I presents the extent to which various FEA methods can be applied to different processing approaches for developing PMBAs. The applicability is qualitatively categorized into three levels. As discussed in Sec. III, the current challenges in PBMA development are summarized in Table II, which evaluates the extent to which different FEA methods address these challenges. The evaluation includes scoring both the effectiveness and feasibility of the five methods against six challenges, with scores ranging from 0, 1, or 2. Applicability is assessed as the product of effectiveness and feasibility. A detailed explanation of the scoring is provided in Secs. IV A–IV E.

A. Non-linear material models

Unlike linear elastic materials, the stress–strain behavior of PBMAs is typically non-linear. The mechanical response is more complex, with regions of elastic deformation, yielding, and strain hardening or softening. Additionally, the material properties depend on the temperature, moisture, and processing conditions.[112] Figure 5(a) shows the typical stress–strain behavior of PBMAs. At lower temperatures, the PBMA exhibits predominantly elastic behavior. The material resists deformation and shows a near-linear relationship between stress and strain at small strains but starts to exhibit strain softening at higher strains. At moderate temperatures, the PBMA exhibits viscoelastic behavior with a combination of elastic and plastic deformation. At higher temperatures, the PBMA becomes softer and exhibits significant plastic deformation. The stress–strain curve shows a lower overall stress for the same strain values, indicating that the material is more compliant and less resistant to deformation as proteins denature and lose structural integrity.

Therefore, non-linear material models are essential for accurately capturing the complex mechanical behavior of PBMAs, particularly as they undergo substantial deformation during processing. According to studies regarding PBMAs and other food proteins like animal meat, these models are particularly useful for addressing challenges related to the creation of texture,[98] chewiness and bite,[103] and texture after heating.[114]

Specifically, for PBMA extrusion processes, e.g., HME, plant proteins are subjected to high shear and temperature, causing significant changes in their structure and behavior.[4,115] The materials exhibit viscoelastic properties, showing both solid-like elasticity and fluid-like plasticity, depending on the local stress and strain conditions.[112] Non-linear material models, such as hyperelasticity,[116] viscoelasticity,[117,118] or plasticity models, have been well developed in mechanical and civil engineering regarding metals, plastics, concretes, etc. for decades, while PBMAs show more complex internal structures and sensitivity to temperature and moisture. Hence, it is crucial to develop non-linear material models for PBMAs, which allows FEA to predict how the material responses under different processing conditions.

B. Advanced rheological models

Similar to meat, proteins used in PBMA exhibit non-Newtonian flow characteristics, such as shear-thinning, which means that the viscosity decreases with increasing shear rate.[97] PBMAs are typically pseudoplastic [Fig. 5(b)] or Bingham pseudoplastic materials, and the yield stress threshold in PBMAs can vary depending on the specific formulation and processing conditions.[119] For instance, high-moisture PBMAs generally show minimal yield stress, acting more like

TABLE II. Evaluation of applying different FEA methods to address challenges of the PBMA development. The applicability is quantified as ●●● (4), ●●○ (2), ●○○ (1), and ○○○ (0).

	Creation of texture	Juiciness and mouthfeel	Chewiness and bite	Stability of texture during storage	Texture after heating	Variability in plant proteins and target products
Non-linear material models	●●●	●●○	●●●	●●○	●●●	●●○
Advanced rheological models	●●●	●●○	●●●	●●○	●●○	●●○
Coupled multi-physics models	●○○	●●○	●●○	●●○	●●○	●●○
AMR	●●○	○○○	●●○	○○○	●●○	●●○
Hybrid approaches combined with FVM, SPH, or LBM	●●○	●●○	●●○	●●○	●●○	●●○

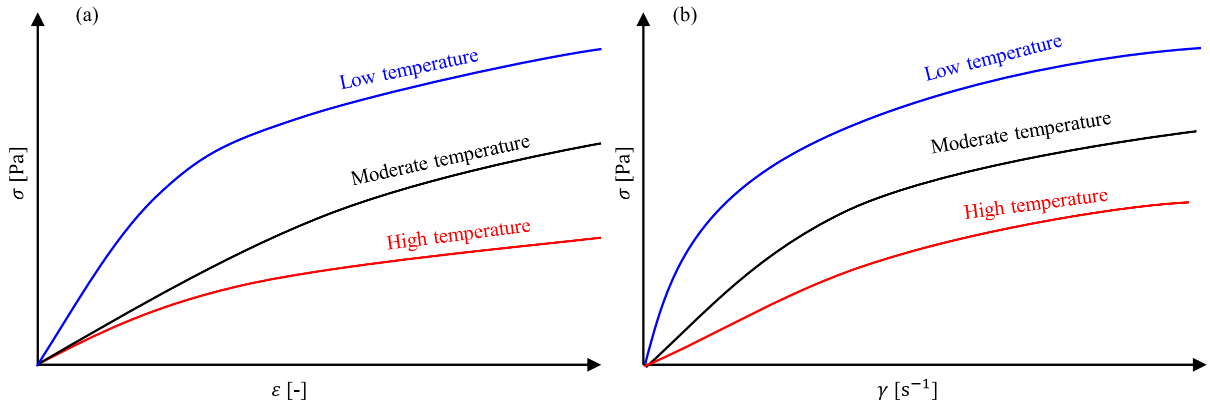

FIG. 5. Schematic of the non-linear material behavior of typical pseudoplastic PBMAs:[113] (a) stress (σ) vs strain (γ) and (b) stress vs strain rate (γ).

pseudoplastic fluids.[112] While Sec. IV A discussed the quasi-static material properties of PBMA, this section focuses on dynamic properties, i.e., the non-linear relationship between the shear stress and the shear rate.

Taking the shear cell technology as an example, it creates defined shear fields that induce protein alignment and fibrous structuring in PBMAs, mimicking the texture of muscle fibers in meat.[120] During this process, PBMA materials must flow and deform while simultaneously maintaining partial structural integrity, making their flow behavior highly complex and non-Newtonian. According to the related research regarding protein in the field of biomedical engineering,[121–124] these non-Newtonian flow characteristics can be captured by models like the Carreau-Yasuda or Giesekus models.[125]

Advanced rheological models allow FEA to predict and optimize the processing conditions required to achieve specific textures. For example, when applying the Carreau-Yasuda model, FEA simulations can adjust shear rates to control how quickly the PBMA viscosity decreases, thereby determining the optimal shear rate range for protein alignment. This approach is essential for texture creation, as shear-induced alignment is the mechanism behind forming fibrous structures. Similarly, the Giesekus model, with its ability to capture viscoelastic characteristics, is valuable for predicting the degree of structural alignment under high-shear conditions. It can help to fine-tune processing conditions for desirable mouthfeel and chewiness which can be quantified as the product of springiness (elasticity), hardness, and cohesiveness (anti-disintegrability).[99]

These models are also beneficial for addressing variability in plant proteins and target products. Variations in protein sources, such as pea, soy, or wheat gluten, lead to different flow behaviors under shear. For instance, wheat gluten tends to exhibit greater elasticity, while pea protein behaves more fluidly under shear.[13] Using FEA, together with limited number of experiments regarding material property analysis and validation, developers can apply rheological models tailored to each protein type, allowing high-efficiency predictions of how different raw materials will behave under various processing conditions.

C. Coupled multi-physics models

In PBMA production, heat, mechanical deformation, and moisture migration all interact during processing,[67] so integrating coupled multi-physics models, as illustrated in Fig. 6, is also crucial for food processing.[105,126,127] These models can be effective in solving challenges related to the creation of texture, juiciness and mouthfeel, texture and structure after heating, and chewiness and bite.

As for texture creation, especially during the heating process, proteins are subjected to simultaneous thermal and mechanical forces, causing them to align and create fibrous structures.[128] As mentioned in Sec. IV A, the mechanical stress, temperature distribution, and moisture content all interact to form the final texture. FEA, through multi-physics models, can simulate how these interactions unfold in real time.[129] The denaturation of protein and the subsequent formation of a fibrous network can be predicted by solving both heat transfer and mechanical stress equations simultaneously. For example, thermal elastic-plastic and viscoelastic-heat transfer models can simulate how the protein material deforms and flows under high temperature and pressure, helping create layered meat-like textures.[130,131]

In addressing juiciness and mouthfeel, moisture migration within the protein matrix directly affects the product's juiciness, as moisture moves due to both thermal gradients and pressure differences.[132,133] By simulating the movement of water, coupled with the heat transfer and mechanical changes in the protein matrix, FEA can help developers predict how juiciness will be impacted under different conditions.[130,134] For instance, thermo-hygro-mechanical models,[135] which model moisture as a function of thermal gradients and mechanical pressure, can be applied to predict how much moisture is retained and released, since it directly impacts juiciness and sensory perception of PBMAs.

It should be noted that there have been many CFD (FVM) studies regarding multi-phase or constitutive flow of moisture migration in food processing.[93,136–139] These studies mainly focused on moisture migration behaviors during processing, as they can notably affect the juiciness and storage stability, while the FEA focuses on resolving the structural response and stress distribution of food materials. Potential possibilities of integrating these approaches into the FEA of PBMAs are discussed in Sec. IV E.

D. Adaptive mesh refinement (AMR)

AMR is a powerful computational tool that dynamically adjusts the mesh resolution in regions where higher accuracy is required.[140] This method can be useful in PBMA processing, where sharp gradients in temperature, velocity, and stress occur, especially near extruder walls or

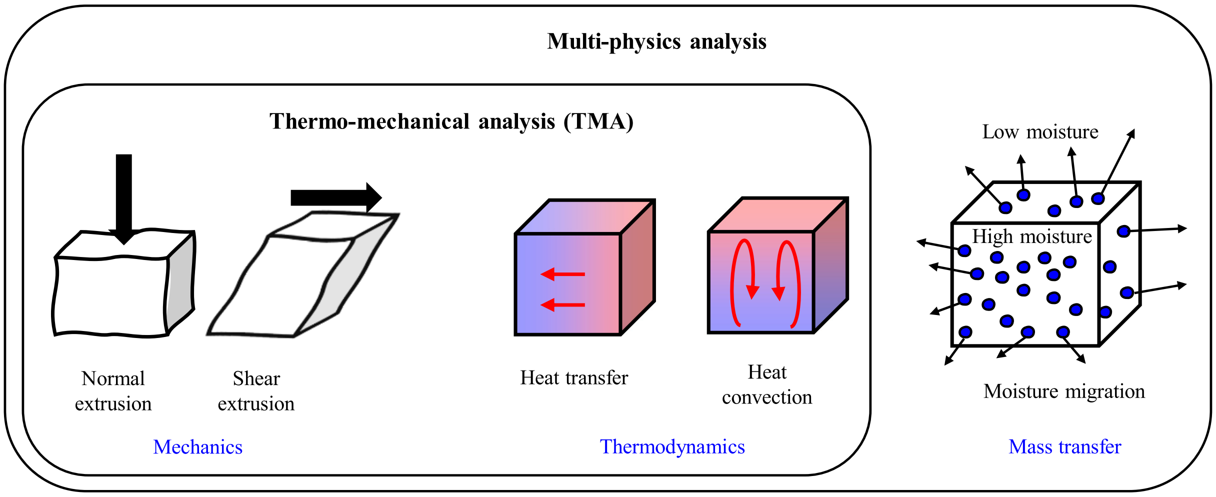

FIG. 6. Schematic of multi-physics analysis coupling mechanics, thermodynamics, and mass transfer.

during rapid phase transitions. Proven by related studies regarding soft matter physics,[141] AMR is particularly applicable in addressing challenges such as texture creation, moisture migration, and texture after heating.

For example, one of the most significant challenges in extrusion-based 3D printing is achieving consistent and precise layer deposition.[142,143] The material undergoes deformation as it is extruded, which requires highly accurate simulations of the shear and normal stresses imposed on the protein matrix.[144,145] Meanwhile, as mentioned in Secs. IV A and IV B, the flow behavior of plant proteins is complex, often exhibiting non-Newtonian and shear-thinning properties. Thus, the protein materials experience sharp velocity gradients and high shear rates as they pass through the nozzle, which influences their alignment and mechanical properties in the final printed structure.[146–148] By refining the mesh around the nozzle exit and the contact region between newly deposited layers and the previous layers, where mechanical forces are concentrated, the simulation can accurately capture the localized stress and strain fields that influence layer adhesion and layer height consistency.[149] In addition, as the extruded material cools and solidifies upon deposition, these refined regions also allow the simulation to predict potential deformation and misalignment of layers more accurately. In general, AMR allows for accurate simulations of the soft matter behavior without overloading the computational requirements.

More specifically, during the 3D printing of a plant-based meat structure with intricate internal layers to simulate muscle fibers, AMR can adaptively increase resolution in these regions, allowing the simulation to predict stress buildup, thermal shrinkage, and potential deformation with high accuracy. This targeted refinement ensures that the FEA model can capture the local mechanical behavior and potential weak points, helping to design printing paths and supports that enhance structural stability.

E. Hybrid approaches combined with FVM, SPH, or LBM

Hybrid computational approaches, which combine FEA with methods such as FVM, SPH, or LBM, can potentially provide a means of capturing the complex, heterogeneous nature of PBMAs.

PBMAs are complex, heterogeneous materials, typically consisting of protein (solid-like) and oil or water phases (fluid-like), which together create multi-phase systems.[3,36,67] FEA excels at resolving the solid-like mechanical behavior of protein structures, while FVM is better suited for capturing the fluid-like movement and distribution of oil and moisture phases within the matrix.[138] In this context, the arbitrary Lagrangian–Eulerian (ALE) techniques provide a flexible framework that can capture large deformation of solid-like components by using FEA, while accommodating the flow of liquid-like components modeled by FVM.[92,150] This is essential for simulating texture creation and variability in plant proteins, where proteins align to form a fibrous structure while oil migrates and lubricates the matrix. Fluid–structure interaction (FSI) methods,[151] such as surface morphing and the immersed boundary method (IBM),[152] can also be beneficial in PBMA applications where the interface between solid- and fluid-like phases plays a central role.[153] Two-way coupled FSI is advantageous for modeling chewiness and bite, as it can capture the deformation of oil pockets within the protein matrix under mechanical forces, closely resembling the textural experiences of meat.

It should be noted that both FVM and FEA are based on the assumption of continuity, meaning that matter can be continually subdivided into infinitesimal elements with local material properties defined at any particular point. Therefore, FEA is on the macroscopic level, i.e., a top-down approach, focusing on macrostructural manipulation for PBMAs, such as extrusion processes, where bulk material properties are altered to create meat-like textures. On the other hand, although FEA is traditionally associated with macroscopic mechanics, by combining FEA with LBM or SPH, it also shows the potential for modeling microscale interactions which are critical in bottom-up approaches. SPH and LBM are particle-based methods suited to capturing mesoscopic-scale interactions between moisture and protein structures.[154,155] They can provide insights into how water migrates within the microstructure of PBMA, influencing texture and mouthfeel.[156] SPH, a particle-based method, is particularly well-suited for simulating flow behaviors at the microscopic scale, where the discrete nature of moisture migration within the protein structure significantly influences texture.[157–160] This is beneficial for simulating juiciness and mouthfeel, as SPH is useful in capturing discrete moisture transport in protein matrices by simulating micro-channel flow and moisture retention in fibrous structures. Meanwhile, LBM can provide a powerful tool for simulating the mesoscale flow of fluids within complex geometries, which is important for understanding moisture migration and its influence on texture creation stability during storage.[156,161] By coupling LBM with FEA, it becomes possible to model how water moves through the protein network at a finer scale, considering mesostructural constraints. This multi-scale approach enables a more detailed understanding of how moisture migration affects the internal structure, which is particularly valuable for achieving a consistent and meat-like texture, especially after heating or storage.

V. FUTURE PERSPECTIVES

The application of FEA in developing PBMAs presents substantial opportunities. Future research should prioritize refining non-linear rheological models that capture specific behaviors such as shear thinning and viscoelasticity, to accurately simulate the complex behavior of plant proteins during processing. In addition, the integration of multiphysics models, which couple mechanical deformation with thermal transfer and moisture migration to account for how temperature and moisture influence protein structuring, is also essential for a comprehensive understanding of plant protein behavior under various conditions. Hybrid computational approaches, combining FEA with techniques such as CFD, SPH, or LBM, could significantly enhance simulation accuracy by optimally capturing heterogeneous textures and multi-phase properties, particularly during extrusion processes.

Emerging technologies, such as machine learning (ML), especially physics-informed neural networks (PINNs), hold promise for enhancing FEA applications in PBMA development. ML can process large datasets from FEA simulations and experimental trials to detect complex ingredient interactions and ideal processing parameters, optimizing ingredient selection, processing parameters, and final product characteristics with greater efficiency than traditional methods. By integrating ML into the FEA workflow, researchers can achieve continually refined predictive insights that improve product formulation and product quality over time.

Interdisciplinary collaboration among food scientists, physicists, and computer-aided engineering (CAE) researchers is encouraged to accelerate the development of plant-based meat products that meet environmental sustainability goals and consumer expectations. Establishing general methodologies for computational modeling and experimental validation can further ensure consistency and reproducibility in PBMA production.

VI. CONCLUSIONS

Achieving the texture of animal meat in plant-based meat analogs (PBMAs) requires sophisticated processing methods and a deep understanding of plant protein behavior. High-moisture extrusion (HME), shear cell technology, and extrusion 3D printing are promising techniques, yet significant challenges remain regarding the consistency and stability of the texture of PBMAs. Meanwhile, finite element analysis (FEA) offers a powerful tool to complement experimental methods, allowing for the simulation and optimization of protein structuring processes.

This study comprehensively examines the application of FEA as a promising computational tool to address the challenges of developing the fibrous texture in PBMAs. It explores various FEA methods to simulate and optimize the complex mechanical, thermal, and mass transfer behaviors inherent in PBMA processing. This study discussed how FEA can replicate the fibrous structure of meat, enhance texture consistency, and mitigate variability in plant protein sources.

By incorporating advanced material models, rheological behavior, and multi-physics simulations, FEA has the potential to accelerate the development of PBMAs that are closer in quality to traditional animal meat. Continued innovation in computational modeling, processing techniques, and interdisciplinary collaboration will play a vital role in the future of plant-based meat production. Embracing new technologies, such as machine learning (ML) for predictive modeling and process optimization, could further enhance the efficiency and scalability of PBMA production, ultimately leading to products that meet consumer expectations for taste, texture, and sustainability.

This study emphasizes the potential of FEA to complement experimental approaches, enabling more efficient and sustainable production of high-quality PBMAs with sensory properties comparable to traditional animal meat. It should also be mentioned that despite its contributions, this study has certain limitations which can be addressed in future research. For instance, the methods for analyzing the interaction between protein and lipid, which plays a crucial role in determining the juiciness and mouthfeel of PMBAs, are not explicitly considered.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Jingnan Zhang: Conceptualization (equal); Methodology (lead); Project administration (lead); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Heng Zhu:** Conceptualization (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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