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Customized 3D Printing of Plant-based Artificial Meat

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Abstract

In recent years, with the continuous increase in consumers' demands for personalized nutrition and sensory experiences, the homogenization issue of traditional plant-based meat has become increasingly prominent. This paper systematically reviews the advancements in the application of 3D printing technology in the customization of plant-based meat, focusing on the analysis of three key technical aspects: precise control of material rheology, multi-material co-printing and structural bionic processes, as well as targeted nutrition enhancement. Research indicates that by establishing a "material-process-structure" collaborative optimization framework, it is possible to effectively achieve biomimicry of muscle texture, targeted nutrition distribution, and customized texture, meeting the specific needs of diverse groups such as the elderly and athletes. However, this technology still faces bottlenecks in the industrialization process, such as multi-material interfacial delamination, low printing efficiency, and insufficient sustainability assessment. In the future, efforts should be made to develop intelligent responsive materials, high-speed multi-nozzle printing equipment, and conduct in-depth life cycle assessments to promote the technology from the laboratory to the market, realizing a new model of personalized and sustainable food manufacturing.

Keywords

3D printing, customized plant-based meat, protein ink, structural biomimicry, material-process synergy

1. Introduction

The global food system is facing extremely severe sustainability challenges. According to data from the Food and Agriculture Organization of the United Nations (FAO), traditional livestock farming accounts for approximately 14.5% of global greenhouse gas emissions and consumes 30% of the world's ice-free land area.Against this backdrop, plant-based artificial meat, as a key alternative solution, has received widespread attention. According to the analysis of MarketsandMarkets, its market size is expected to exceed 24 billion US dollars by 2027 (Markets., 2025). However, studies have pointed out that the products currently manufactured using mainstream extrusion technology have certain limitations: for example, homogenous structure, inability to precisely control nutritional components, and difficulty in meeting the sensory and health needs of diverse populations. These issues have become critical factors restricting industrial upgrading and market acceptance (Gu et al., 2023, Zhao et al., 2022). 3D printing technology, with its unique spatial precision positioning capability, offers a revolutionary solution to break through the aforementioned bottlenecks. By controlling the deposition behavior of materials at the micrometer scale, it can achieve biomimetic muscle fiber bundles, on-demand distribution of nutrients, and the creation of customized complex geometric shapes (Bhuiyan et al., 2025, Tong et al., 2024). The advancement of this technology is not only pivotal for the paradigm shift in food manufacturing but also provides a critical strategic pathway toward achieving efficient resource utilization and personalized nutrition under the United Nations Sustainable Development Goals (SDGs).

Although existing research has made certain progress in the rheology of protein inks and the interface fusion of multi-material co-printing, there are still key contradictions: the systematic integration of “material-process-structure-function” is still relatively superficial, and the improvement of printing accuracy often comes at the expense of nutrient active components, while excessive addition of rheological modifiers may lead to deterioration of texture (Bhuiyan et al., 2025).

There has been no systematic review of the customization of plant-based artificial meat through 3D printing. Therefore, this article aims to conduct a comprehensive analysis of the synergistic coupling of the technology chain for the customization of plant-based artificial meat through 3D printing, and also critically assess the practical path for its industrialization. Furthermore, this review focuses on the logic of cross-scale collaborative optimization, clarifying the transmission mechanism from molecular design to macroscopic product properties, with the aim of providing a theoretical framework to bridge the gap between laboratory innovation and large-scale production.

2. Key Technologies for 3D Printing Customization

3D printing customization encompasses a range of technologies, including rheological control and functional delivery mechanisms, as well as structural biomimicry construction and multi-material printing strategies. Key techniques primarily involve protein ink systems and rheological control, microencapsulation technology, liposome embedding technology, multi-material co-printing technology, and structural biomimicry processes.

2.1 Rheological Control and Functional Delivery Mechanisms

2.1.1 Protein Ink Systems and Rheological Control

The rheological behavior of plant-based protein inks is a critical factor determining their suitability for 3D printing and the structural integrity of the final product. In recent years, plant-based proteins, particularly those derived from pea protein and edible fungal protein, have been extensively studied due to their unique rheological properties.Pea protein exhibits significant shear-thinning(the viscosity of a fluid decreases as the shear rate increases) behavior , which facilitates smooth flow during ink extrusion and rapid viscosity recovery after deposition, thereby ensuring printing accuracy and shape retention capabilities (Zhang et al., 2022).Edible mushroom protein, with its excellent water-holding capacity, can endow printed products with a tender and juicy texture, significantly improving their taste. Additionally, emerging protein sources like black soldier fly protein and microbial proteins (such as Fusarium venenatum) are regarded as promising raw materials due to their high fiber-forming potential. However, their rheological control mechanisms and Printability still require systematic investigation (Chao et al., 2025, Ou et al., 2023).

To better optimize printing performance, the application of rheological modifiers becomes particularly critical.Studies have shown that gellan gum, at an addition level of 0.4%, can significantly improve the printing performance of the ink by forming a three-dimensional network structure, enhancing printing accuracy by nearly 27.8%; however, excessive addition can lead to a significant increase in extrusion resistance, highlighting the importance of a “dose-performance” balance in rheological control (Zhang et al., 2022). Other hydrocolloids and dietary fibers are also commonly used to modulate the thixotropic behavior of the ink to achieve the best match between extrusion smoothness and shape retention ability. It is important to note that the rheological properties of the ink directly determine its printability and, consequently, influence the selection of key process parameters, including matching the nozzle diameter with the ink’s yield stress(the maximum stress a material can withstand before undergoing plastic deformation under an applied force), and dynamically adjusting the extrusion pressure based on its shear viscosity.

2.1.2 Targeted Delivery and Stability Enhancement of Functional Components

In terms of functional component delivery, microencapsulation technology is widely used to improve the stability of active ingredients during the printing process and their controlled release performance in the final product. For instance, the application of microencapsulated heme peptide has improved the color stability of plant-based meat products by 40% after heat treatment, with the core material release rate controlled below 5%, significantly enhancing the authenticity of the product's color (Xue et al., 2024).Liposome embedding technology is employed to protect volatile flavor substances, achieving a retention rate of over 85% even at printing temperatures as high as 180°C, demonstrating significantly superior thermal stability compared to direct addition methods (Ludwig et al., 2021).Moreover, nutritional fortifiers such as vitamins, minerals, and prebiotics are often encapsulated in multilayer microcapsules made of sodium alginate or chitosan to achieve spatiotemporally targeted delivery. However, when the addition amount exceeds 5%, it may exert non-negligible effects on the viscoelastic properties of the ink, potentially leading to layer separation or deformation during printing.

The core challenge in this field lies in the synergistic design between the incorporation of functional components and the rheological properties of the ink. The introduction of functional components often alters the rheological properties of the ink, necessitating systematic optimization within a "rheology-formulation" coupling framework .For instance, the thickening effect induced by the microcapsule wall material needs to be compensated by appropriately reducing the protein concentration; simultaneously, the temperature gradient during the printing process and post-processing treatments also directly affect the encapsulation integrity and final release behavior of functional components. Therefore, achieving efficient and stable functional delivery requires overcoming the dual barriers of material formulation design and printing process optimization, with solutions relying on the integration of multidisciplinary approaches and systematic innovation.

2.2 Structural Biomimicry Construction and Multi-Material Printing Strategies

Multi-material co-printing technology is a key approach to achieving structural biomimicry in plant-based artificial meat, with its core objective being the simulation of the alternating distribution characteristics of muscle and fat in natural meat .There exists a significant trade-off relationship between temperature control for fiber structure formation and nutrient preservation.In the realm of multi-material co-printing, researchers have achieved alternating deposition of muscle and fat analogs using a dual-nozzle system.Muscle analogs are typically based on inks with high pea protein content, while fat analogs often utilize systems rich in rice bran oil emulsions.

Studies have shown that high-temperature printing can effectively promote the fiber orientation of pea protein, achieving an orientation degree exceeding 0.75, thereby better mimicking muscle texture. However, this process leads to over 60% loss of heat-sensitive nutrients such as vitamin C. In contrast, while low-temperature printing can preserve approximately 90% of nutritional components, it struggles to achieve the desired fibrous texture, limiting the product's sensory authenticity (Chao et al., 2025, Wang et al., 2025). Simultaneously, multi-material co-printing faces two core challenges: rheological matching and interfacial delamination. If heterogeneous materials have incompatible rheological properties—particularly when their yield stress differs by more than 50 Pa—it can easily cause interlayer slippage during printing, with displacement potentially exceeding 200 μm, severely compromising structural integrity (Tong et al., 2024). Additionally, insufficient interfacial bonding strength between materials can trigger delamination. To address this issue, researchers have adopted an in-situ enzymatic cross-linking strategy. For example, adding 0.5 U/g of transglutaminase can increase interfacial adhesion strength by 3.2 times. Combined with temperature gradient control, this approach can induce hydrophobic interactions, further reducing the risk of delamination (Zhang et al., 2022). Studies have shown that TG enzyme (transglutaminase)-mediated lysine cross-linking can increase the interfacial bonding strength between muscle and fat analogs to 12.5 kPa, approaching the 15.2 kPa observed in real meat, significantly enhancing the product's textural authenticity (Zhang et al., 2022).

3. Context Adaptation and Technical Pathways

3.1 Precision Nutrition Customization to Meet Diverse Health Needs

The core strength of 3D printing customization technology for plant-based artificial meat lies in its ability to precisely adapt the product's composition, structure, and function to the physiological characteristics and nutritional requirements of different groups. In terms of precision nutrition customization, this technology demonstrates significant application potential. Taking the elderly population as an example, their nutritional needs focus on high protein intake, textural properties that are easy to chew and swallow, as well as fortification with calcium and vitamin D. Studies have shown that by regulating the rheological properties of printing inks combined with soft texture design, the compound annual growth rate (CAGR) of product palatability can reach 7.7%. Simultaneously, the use of microencapsulation technology enables precise spatial positioning of nutrients, allowing for the enrichment of calcium and vitamin D in easy-to-chew regions, thereby balancing sensory experience and nutritional efficacy (Wang et al., 2025, Rocha et al., 2021).

For athletes, their nutritional strategies should emphasize a high proportion of branched-chain amino acids (BCAAs), zoned optimization of energy density, and timely supplementation of electrolytes. By leveraging multi-material co-printing technology, regional control of nutritional density can be achieved. For instance, a core layer with high BCAA (branched-chain amino acid) content, typically reaching 50% or higher, can be combined with an outer shell layer rich in carbohydrates to synergistically promote post-exercise recovery and energy supply (Wang et al., 2025).

For individuals with specific medical conditions, there are strict limits on the sodium, sugar, and fat content in their food, while requiring an increased intake of dietary fiber and bioactive compounds.3D printing technology enables precise control over the spatial distribution and proportional addition of various components, allowing active ingredients to be embedded directionally within a high-fiber matrix while maintaining low sodium, low sugar, and low fat content. This achieves functional enhancement without compromising sensory quality (Rocha et al., 2021).For the children's demographic, in addition to meeting basic nutritional balance requirements, there is also a need to incorporate fun eating experiences.By combining free-form printing technology with surface flavor embedding techniques, it is possible to ensure the supply of essential nutrients while enhancing the product's visual appeal and flavor complexity, thereby promoting children's acceptance.

3.2 Sensory and Culinary Innovation

In terms of sensory and culinary innovation, 3D printing technology enables high-fidelity simulation of the complex structures of natural meat through precise programming of multi-material deposition paths. For example, by controlling the deposition frequency of fat analogs and combining it with heat-enzyme co-processing, the simulation degree of the marbling pattern of plant-based artificial meat exceeds 90%, significantly improving its flavor release and juiciness retention during cooking (Tong et al., 2024, Zhang et al., 2022). Moreover, this technology enables the rapid formation of complex topological structures(a mathematical concept describing spatial properties and organization), which not only expands creative possibilities in dish design but also optimizes heat conduction efficiency, thereby enhancing the final product's eating quality. The regional customization of flavors further enriches the sensory experience. For instance, by embedding micro-encapsulated smoky or herbal flavors between layers, a "multi-layered flavors in a single bite" effect is achieved, catering to the high-end dining market's pursuit of personalization and experiential dining.

4. Bottlenecks in Technology Transfer and the Ecological Compatibility Mechanism

The customized 3D printing technology for plant-based meat is still facing multiple challenges on its path to commercialization, requiring breakthroughs in technological, ecosystem, and market acceptance bottlenecks. The core technical challenge is predominantly manifested in the prevalent issue of interface delamination during multi-material co-printing. This severely restricts the product's structural integrity and sensory realism, resulting in qualification rates consistently below 70% (Bhuiyan et al., 2025, Ludwig et al., 2021).The optimization of in situ cross-linking processes is regarded as a critical pathway to enhance interfacial adhesion strength. Meanwhile, the printing efficiency of current mainstream equipment generally falls below 50 g/h, which is far insufficient to meet the demands of commercial-scale production and has become a major technical barrier to capacity expansion (Bhuiyan et al., 2025, Ludwig et al., 2021).

Ecological sustainability is an unavoidable consideration in the implementation of technology. Although plant-based ingredients offer environmental advantages over traditional animal husbandry, their own environmental footprint still needs to be further reduced. For instance, the production process of mainstream pea protein, a key raw material, generates a carbon footprint of approximately 2.5 kg CO_2-eq/kg (Zhang et al., 2022). Developing biomass-based inks derived from agricultural by-products has been proven to be an effective approach to reducing the environmental burden, potentially lowering the carbon footprint by 35%. However, systematic life cycle assessment (LCA) for plant-based 3D-printed artificial meat remain severely lacking, with the coverage of relevant databases below 30%, making it difficult to comprehensively and objectively quantify its environmental benefits and guide sustainable design.

Market acceptance poses another major challenge. The flavor gap is considered the main difference between current products and traditional meat. A consumer report by the globally renowned alternative protein promotion organization GFI (2025) clearly states that 73% of potential consumers view taste as the primary obstacle to trying plant-based meat. Meanwhile, consumers have significant concerns regarding the long-term health impacts of emerging food processing technologies, particularly 3D printing. A global survey by FMCG-Gurus (2025) shows that approximately 65% of consumers hold reservations about this technology (Rocha et al., 2021, Schreuders et al., 2021). These cognitive barriers, intertwined with technical and cost issues, collectively affect the product's market penetration rate .

To break through the aforementioned bottlenecks, a collaborative breakthrough approach is required. In terms of material modification, the focus lies in developing novel composite systems to significantly enhance the interfacial compatibility among multi-materials, thereby effectively suppressing delamination. At the process optimization level, the core objective is to develop high-speed, multi-nozzle array printing platforms, aiming to boost production efficiency beyond 200 g/h to meet the economic demands of large-scale production. Ecological compatibility design must be integrated throughout the entire process of material selection and process development to continuously reduce the overall environmental footprint of the technological system. Regarding market acceptance, the priority is to narrow the flavor gap by employing precise flavor simulation technology to enhance the similarity between plant-based meat and conventional meat, thereby overcoming the 73% potential consumers' reluctance to try (Rocha et al., 2021, Schreuders et al., 2021).

5. Conclusion

This paper systematically reviews research progress in the field of 3D printing customization of plant-based artificial meat, highlighting the technology's significant potential in achieving structural biomimicry, nutritional personalization, and enhanced sensory qualities through precise control of material rheology, multi-material co-printing, and structural biomimetic processes. Its core breakthrough lies in establishing a synergistic "material-process-structure" framework, elucidating the decisive role of material rheology in process feasibility and demonstrating how process parameters directly regulate the functional realization of the final product. The synergistic framework for 3D printing technology, constructed based on advancements in the customization of plant-based artificial meat, provides core theoretical support for subsequent research. First, the coupled material-process-structure model lays a theoretical foundation for quantitatively analyzing multi-physics interactions during printing. This model can guide the development of predictive mathematical models to optimize ink formulations and process windows in the future. Second, key data accumulated from practical studies offer direct references for process standardization, particularly in guiding the setting of rheological parameter matching thresholds for multi-material compatibility design. More importantly, case validations targeting precise nutritional customization underscore the unique practical value of this technology in addressing personalized health needs, providing technical support for the transition of food manufacturing from "mass production" to "on-demand customization."

Current research still faces numerous bottlenecks: the issue of multi-material interfacial delamination requires breakthroughs in in-situ cross-linking technology; printing efficiency severely restricts industrialization; safety assessment systems for novel ingredients and international regulatory frameworks for customized products remain entirely absent. These shortcomings directly hinder the large-scale implementation of the technology and the process of market standardization .

Future breakthroughs need to focus on three key directions: 1. Material level: Develop composite protein ink systems with intelligent responsiveness and environmentally friendly characteristics to expand functionality and reduce environmental footprint. 2. Process level: Build high-speed, multi-nozzle printing platforms integrating wet-spinning fiber and cell structure biomimetic strategies. 3. Industrial level: Establish interdisciplinary standardization systems, promote regulatory oversight and safety assessment of personalized food products, and enhance public acceptance of their taste. Advancing these research areas will not only fill the gaps in multi-scale structural regulation theory but also drive innovation in regulatory science, ultimately enabling a substantive leap of the technology from the laboratory to the consumer market and reshaping the future landscape of the food industry.

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