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Mechanism, Classification and Application of Edible Bioinks for 3D Bioprinted Cultured Meat

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Abstract. Traditional livestock farming consumes massive land and water resources while generating enormous greenhouse gas emissions, and large-scale animal slaughter also brings continuous global disputes over animal welfare and food supply security. Electrohydrodynamic three-dimensional bioprinting technology can construct highly ordered fibrous tissue structures at nanoscale precision, effectively overcoming the loose structural defects of traditional static cell scaffolds applied for cultured meat manufacturing. This paper systematically sorts current mainstream edible bioprinting raw materials into three distinct categories including plant derived, microorganism derived and synthetic composite bioinks, and fully compares their inherent printability, cell compatibility, sensory performance and existing industrial bottlenecks alongside universal material modification strategies such as physical blending and peptide grafting. Plant derived bioinks with natural fibrous architectures can well mimic the texture of native livestock meat but carry unavoidable allergen risks and unstable raw material quality. Microbial polysaccharide bioinks feature low production costs yet lack natural cell binding sites to restrict long-term myogenic maturation. Synthetic composite materials realize controllable molecular tuning, while high synthesis and purification costs limit large-scale popularization. This work establishes a multi-dimensional evaluation framework for edible bioink performance and provides systematic theoretical references for the development of low-cost, high-bionic industrial cultured meat production technologies.

Keywords: T Cultured meat, 3D printing, bioink, edible scaffold

1. Introduction

Large-scale livestock farming occupies abundant land and water resources and releases substantial greenhouse gas. Slaughter-based meat supply also brings widespread ethical controversies on animal welfare. Cultured meat technology provides sustainable protein production routes consistent with carbon neutrality targets. Electrohydrodynamic bioprinting achieves nanoscale precise construction of ordered fiber structures and overcomes loose texture defects of traditional static cell scaffolds [1]. Edible bioinks serve as core printing raw materials. Their rheological behaviors, cell compatibility and food safety decide the final quality of cultured meat products. Different from biomedical hydrogel printing materials, raw substances for meat manufacturing need full edibility and

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controllable low production cost and form unique research boundaries separated from medical biomaterials.

Overseas research teams take the lead in developing plant protein printing raw materials. Scholars have completed cell co-culture verification of textured soy protein and pea protein substrates and built mature evaluation systems for mechanical and sensory indicators. Relevant studies also explore peptide grafting to raise cell attachment efficiency, yet most existing papers analyze single material without horizontal comparison across multiple raw material systems. Domestic research focuses on composite hydrogels prepared from microbial polysaccharides and agricultural byproducts. Local researchers optimize printing formulas of gellan gum and carrageenan and conduct targeted exploration matching domestic crop resource characteristics. Domestic published papers lack unified multi-indicator evaluation criteria and fail to integrate plant microbial and synthetic printing materials into a complete comparative framework [2].

Current published papers mostly discuss single printing material without systematic classification of three mainstream raw material types. Universal composite modification strategies for different bioink systems also receive insufficient summarization. This paper classifies edible bioprinting raw materials according to material sources and compares their printing performance, cell culture effects and industrial bottlenecks, then sorts mainstream blending and peptide grafting optimization methods. The final section summarizes research deficiencies and proposes forward industrial research directions to build a complete research chain covering material sorting performance comparison and industrial application prospects.

2. Plant-derived edible bioinks

Plant-derived bioinks represent the most widely studied raw material system for cultured meat substrates. Such materials realize industrial transformation away from animal-sourced biomaterials with high immunogenic risks. Their core advantages originate from synergistic interactions between plant proteins and polysaccharide components to construct three-dimensional microenvironments matching rheological and mechanical features of natural muscle tissue. Eligible printing raw materials fall into two major groups, including high-strength fibrous protein materials and decellularized plant tissues with inherent vascular channels.

2.1. Bioinks with high-strength fibrous protein structures

Textured soy protein (TSP) is a mature porous plant biomaterial verified to support attachment and proliferation of bovine muscle cells, capable of constructing complete 3D bovine muscle and adipose tissue models. In triple co-culture systems of bovine satellite cells, smooth muscle cells and endothelial cells, TSP scaffolds significantly promote muscle tissue formation and extracellular matrix deposition. Mechanical tests demonstrate that TSP scaffolds seeded with bovine muscle cells exhibit Young's modulus and ultimate tensile strength equivalent to native bovine skeletal muscle. Organoleptic blind trials prove that cell-laden TSP samples present authentic meat aroma and fibrous texture indistinguishable from conventional meat products [1].

Pea protein is another mainstream plant protein bioink raw material. Pea protein blended with alginate modified by RGD adhesion peptides forms porous hydrogels with strong water retention capacity, which facilitates nutrient and oxygen transport inside scaffolds while accelerating metabolic waste removal. Mechanical testing results reveal pea protein composite scaffolds possess elasticity far superior to pure alginate groups, whose mechanical properties are closer to juvenile bovine semitendinosus muscle, showing stable structural performance during long-term culture [2].

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Cereal prolamins including corn zein, wheat gliadin, barley hordein and rye prolamin, are printable via EHD technology to form pure fibrous edible scaffolds. In vitro cell culture tests confirm mouse C2C12 myoblasts and porcine satellite cells efficiently adhere, proliferate and fuse into muscle fiber bundles on prolamin matrices. The self-assembled fibrous structure of prolamin eliminates additional crosslinking treatment requirements, simplifying printing processes. The prominent industrial limitation lies in plant protein allergy risks for sensitive consumer groups, restricting market popularization [3].

2.2. Decellularized plant tissue bioinks with natural vascular networks

Decellularized vegetable tissues retain inherent interconnected vascular pipelines and serve as low-cost edible scaffold carriers. Spinach decellularized matrix has prominent cost and raw material supply advantages, and the food-grade preparation process does not require strict residual DNA removal standards for medical implants. After 14 days of bovine satellite cell culture, the total cell viability of decellularized spinach scaffolds has no statistically significant difference compared with gelatin control groups. The built-in multi-branched vascular network solves the internal oxygen diffusion barrier of dense scaffolds, guiding ordered alignment of muscle cells to simulate natural meat fiber arrangement [4].

Lotus root and petal fibers after decellularization treatment can be processed into natural plant fiber printing materials. Lotus fiber substrates support large-scale cultivation of porcine muscle stem cells and form highly aligned fiber bundles mimicking layered pork belly structures. Nutrient detection proves muscle tissues cultured on lotus fibers contain complete essential amino acid compositions equivalent to conventional pork products. Composite stacking of muscle and adipose layers can reach five-centimeter tissue thickness after continuous incubation [5].

3. Microorganism-derived edible bioinks

Microbial bioinks adopt food-safe polysaccharide metabolites secreted by microorganisms rather than crude microbial biomass. Such hydrogel materials carry adjustable gelation capacity and extrusion rheological properties and can be divided into four subgroups, including microalgae, macroalgal polysaccharides, bacterial exopolysaccharides and fungal mycelium materials. Different from plant protein substrates with intrinsic fibrous texture, microbial polysaccharide matrices lack natural cell binding sequences. Targeted compound blending with plant proteins or adhesion peptides serves as the most mature optimization approach to promote long-term myogenic differentiation.

3.1. Microalgae-derived bioink raw material

Microalgae strains such as Auxenochlorella protothecoides contain abundant intracellular protein and polysaccharide components that can be crushed and screened into low-cost printing additives. Adding thirty-six weight percent microalgae powder into alginate raw materials adjusts printed product texture to simulate aquatic meat structures and cuts down overall material expenses [6]. Microalgae composite printing materials face obvious industrial obstacles. Natural algal pigments lead to dark green finished products inconsistent with livestock meat color. Intrinsic fishy odor cannot be fully eliminated through conventional deodorization techniques. Current relevant research only focuses on seafood analog products without mature formulas for bovine or porcine cultured meat substrates.

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3.2. Macroalgal polysaccharide bioinks based on κ-carrageena

κ-carrageenan extracted from red algal cell walls is a typical thermoreversible hydrocolloid. Unmodified κ-carrageenan achieves physical gelation triggered by potassium cation coordination, while methacrylated κ-carrageenan (MA-κ-carrageenan) realizes permanent chemical crosslinking under UV irradiation, and the two gelation modes are completely independent and cannot be substituted for each other in printing formulation design. Gradient concentration screening experiments prove that 15 wt% κ-carrageenan aqueous solution reaches the optimal balance of extrusion fluidity and post-print shape retention; scaffolds printed by this formula maintain 97.84 L929 fibroblast viability after two weeks of continuous incubation [7].

Pure carrageenan hydrogel has two obvious defects in the cell culture system. First, the molecular chain does not contain RGD or other cell adhesion motifs, so myoblasts only attach loosely to the gel surface and cannot form dense cell layers inside the scaffold. Second, the hydrogel presents serious swelling and degradation in serum-containing culture medium; with the extension of culture time, continuous water absorption leads to structural dilatation, and the tensile strength drops by more than 60% within 14 days, which cannot support long-term tissue maturation. To offset these deficiencies, domestic and foreign researchers commonly compound carrageenan with pea protein or gelatin at a mass ratio of 4:1, which introduces abundant adhesion sites and slows down the swelling rate of the gel network simultaneously.

3.3. Bacterial exopolysaccharide bioinks: gellan gum

Gellan gum (GG) is a linear anionic polysaccharide secreted by Sphingomonas elodea, a food-safe industrial strain, which has a completely different metabolic pathway from pathogenic Pseudomonas aeruginosa. GG can form rigid crosslinked hydrogel networks under low-concentration calcium ion induction without heating treatment, which greatly simplifies the post-print curing operation of EHD bioprinting [8]. Comparative crosslinking gradient tests set 0.018 M and 0.180 M $CaCl_2$ treatment groups as control variables. High-concentration calcium ions neutralize negative charges on GG molecular chains, eliminate electrostatic repulsion between polysaccharide fragments, and induce myoblasts to form stretched spindle cytoskeletons, which is more conducive to myotube fusion. The optimal composite ink formula is GG-gelatin mass ratio 2:3; gelatin supplements cell adhesion function while regulating the ink's shear-thinning rheological property to adapt to continuous extrusion printing.

Gelatin-gellan composite hydrogels retain stronger water-locking capacity during long term incubation compared with pure carrageenan materials, with nearly half the weight loss rates under identical culture cycles. Single gellan gum raw substances still show weak cell affinity. Current research mixes cereal prolamin or isolated soy protein into GG matrices to optimize printability and myogenic differentiation efficiency synchronously.

3.4. Fungal mycelium composite bioinks

Single fungal mycelium exhibits poor extrusion performance and weak gel-forming ability, and must be compounded with polysaccharide hydrocolloids to meet bioprinting requirements. The mycelium of Stropharia rugosoannulata is selected as the core fibrous raw material; mechanical low-temperature crushing achieves uniform dispersion of filamentous fragments without destroying natural protein structures inside mycelia [9]. Curdlan polysaccharide is added as the reinforcing

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component to enhance intermolecular hydrogen bonding, improving thermal stability and reducing water loss during post-print storage.

Multi-group orthogonal experiments screen optimal composite proportions containing fifty percent mycelium, five percent isolated pea protein and six percent curdlan. This formula carries ideal thixotropy matching electrohydrodynamic printing requirements. Cured gel texture and chewiness highly align with cooked pork belly characteristics. Compared with pure polysaccharide printing materials, mycelium composite substrates introduce internal natural fiber distribution and shorten cell fusion cycles by roughly one week. The primary shortcoming originates from unstable raw material quality. Different fermentation cycles generate inconsistent fiber lengths and cause fluctuating rheological features of prepared printing inks.

4. Synthetic composite edible bioinks

Synthetic composite edible bioinks refer to food-safe hydrogel systems blended from natural edible polysaccharides and artificially modified polymer or peptide substrates. Non-edible medical polymers generating toxic degradation products are excluded from this category. Such materials support precise molecular-level performance adjustment according to printing and cell culture demands and own core advantages in accurate tissue simulation compared with plant and microbial raw substances carrying fixed natural molecular structures. High synthesis and purification expenses alongside immature mass production technologies form major industrialization barriers.

4.1. Food-grade polymer composite hydrogel

Poly (lactic-co-glycolic acid) (PLGA) porous microcarriers with 10–80 μm interconnected pores have excellent cell attachment capacity, but PLGA belongs to medical raw materials without complete food safety certification and cannot be directly applied to edible cultured meat printing [10]. Polypropylene is completely excluded from food ink formulation because of its non-degradable characteristics, which easily produce microplastic residues inside tissue constructs after long-term culture. Food-approved polyvinyl alcohol (PVA) is the mainstream synthetic polymer carrier for edible composite hydrogels, which can be compounded with starch and carrageenan to prepare CSCP serial bioinks [11].

Two standard CS formulations are designed: CSCP-1 (3.0 wt% starch) and CSCP-2 (5.0 wt% starch). Low-starch CSCP-1 forms sparse intermolecular crosslinks, showing higher tensile strength under low strain conditions; high-starch CSCP-2 generates dense starch aggregates, weakening the overall mechanical modulus of the hydrogel. In short-term culture within 7 days, CSCP-2 provides more abundant carbon sources for cells and presents stronger metabolic activity. When the culture cycle is extended to 14–21 days, the dense starch network blocks the internal transport of nutrients and dissolved oxygen, leading to a continuous decline in cell proliferation efficiency.

To balance mechanical performance and cell activity, gradient starch compounding tests are widely adopted in current research, and 4 wt% starch-PVA composite ink is recognized as the compromise optimal formula. Nevertheless, pure PVA-starch composite ink still lacks natural adhesion peptides, and the addition of exogenous RGD fragments is required to improve myogenic differentiation efficiency.

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4.2. Multi-crosslink modified composite ink optimization strategy

Multi-crosslink co-modification represents common optimization logic for synthetic composite printing materials combining physical hydrogen bonding, ion coordination and mild chemical crosslinking to balance printability and long-term structural stability. Natural tannic acid extracted from plant tissues acts as a green crosslinking agent to modify PVA alginate composite systems. Tannic acid molecules form hydrogen bonds with polysaccharide hydroxyl groups and improve hydrogel anti-swelling performance without introducing toxic chemical reagents. Compared with single-ion crosslinked carrageenan or gellan materials, tannic acid co-crosslinked composite hydrogels cut scaffold weight loss rates by over fifty percent under medium immersion tests. Multi-crosslinking regulation adjusts internal pore size distribution and forms interconnected microchannel networks to accelerate oxygen and nutrient exchange and shorten tissue maturation cycles by seven to ten days. Strict dosage screening needs implementation for tannic acid applications. Excessive tannin content inhibits cell proliferation efficiency across different cell strains.

4.3. Artificially modified peptide composite bioinks

Artificial self-assembling peptide hydrogels have outstanding matrix simulation potential, yet most peptide synthesis processes have high cost and partially unmodified fragments have cytotoxic risks [12]. Fmoc-FF peptide combined with TEMPO-oxidized cellulose nanofibrils forms high-strength hydrogels under calcium ion crosslinking. However, free Fmoc groups fall off from the peptide chain during long-term culture, inhibiting myoblast viability; calcium chelation treatment can relieve this toxicity, but the post-processing steps increase industrial production costs significantly.

Food-safe peptide screening platforms based on click chemistry are established to screen low-toxicity adhesion sequences [13]. Comparative 2D and 3D culture verification proves that fibronectin (FN) peptide-modified substrates significantly accelerate myoblast stretching and myotube elongation, while vitronectin (VN) peptide induces spherical cell clusters with weak spreading ability, which cannot support mature muscle tissue formation. Current peptide composite printing materials only suit laboratory small-batch preparation. Large-scale food-grade synthesis and purification technologies remain underdeveloped and restrict mass cultured meat manufacturing applications.

Comprehensive horizontal comparison across three bioink categories reveals clear differentiated application boundaries. Plant-derived raw substances achieve the best sensory simulation effect yet face allergen and raw quality risks. Microbial polysaccharide materials own minimum raw material costs but demand peptide compounding to compensate for insufficient cell binding capacity. Synthetic composite systems realize full performance customization while bearing the highest production thresholds. Single raw material systems cannot simultaneously satisfy requirements on printing properties, cell differentiation, structural stability, production cost and full food safety. Compound modification approaches combining multiple biomaterials become necessary technical paths to offset respective inherent defects of each material category.

5. Conclusion

Edible bioinks function as core foundational raw substances for electrohydrodynamic three-dimensional bioprinting cultured meat and determine sensory quality and industrialization prospects of final meat analog products. This paper divides existing printing raw substances into plant, microbial and synthetic composite three major groups and systematically sorts their material

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features, printing behaviors, cell culture effects and inherent industrial bottlenecks alongside mainstream blending, peptide grafting and multi-crosslink modification strategies. Plant-based materials deliver natural fibrous structures matching native meat texture but suffer allergen and unstable raw quality barriers. Microbial polysaccharide materials cut down overall production expenses yet lack intrinsic cell adhesion motifs to restrict myogenic maturation. Synthetic composite systems support targeted molecular regulation while being limited by high purification and synthesis costs. The integrated sorting framework of this work supplies systematic theoretical references for edible bioink performance optimization and pushes the development of low-cost, highly bionic three-dimensional cultured meat manufacturing technologies.

This paper contains obvious analytical deficiencies. The paper does not expand discussion on animal-sourced edible printing materials, including gelatin and fibrin, despite relevant published experimental data. Quantitative cost comparison data under mid-scale industrial production conditions receive insufficient collation. Adaptation differences of various bioinks under diverse electrohydrodynamic printing equipment also lack targeted sorting and analysis.

Three core research directions deserve priority exploration in follow-up industrial research. Unified multi-indicator evaluation standards covering printability, cell compatibility, sensory performance and manufacturing adaptability need establishment. Novel multi-component composite bioinks integrating the fibrous advantages of plant materials, the low-cost merits of microbial polysaccharides and the precise regulation capacity of synthetic substrates require development. Low-cost, large-scale, food-grade preparation and green modification technologies need optimization to eliminate raw material batch fluctuation and hidden safety risks. Targeted material development matching different livestock meat simulation demands alongside deeper research on green and efficient modification techniques will accelerate large-scale commercialization of three-dimensional bio-printed cultured meat.

References

[1] Ben-Arye, T., Shandalov, Y., Ben-Shaul, S., et al. (2020). Textured soy protein scaffolds enable the generation of three-dimensional bovine skeletal muscle tissue for cell-based meat. *Nat Food, 1*, 210–220. https://doi.org/10.1038/s43016-020-0046-5

[2] Ianovici, I., Zagury, Y., Redenski, I., Lavon, N., & Levenberg, S. (2022). 3D-printable plant protein-enriched scaffolds for cultivated meat development. *Biomaterials, 284*, 121487. https://doi.org/10.1016/j.biomaterials.2022.121487

[3] Su, L., Jing, L., Zeng, X., Chen, T., Liu, H., Kong, Y., Wang, X., Yang, X., Fu, C., Sun, J., & Huang, D. (2023). 3D-printed prolamin scaffolds for cell-based meat culture. *Adv. Mater, 35*, 2207397. https://doi.org/10.1002/adma.202207397

[4] Jordan, D. J., Alex, S. R., & Glenn, R. G. (2021). Decellularized spinach: An edible scaffold for laboratory-grown meat. *Food Bioscience, 41*, 100986. https://doi.org/10.1016/j.fbio.2021.100986

[5] Wu, Y., Li, Y., Yang, Q., He, C., Tang, J., Shi, L., Dai, J., & Zhang, C. (2025). Lotus fiber-derived scaffolds for enhanced cultured meat production: Quality and sustainability. *Bioactive Materials, 51*, 807-824. https://doi.org/10.1016/j.bioactmat.2025.06.048

[6] Park, S. M., Ryoo, J. H., Kwon, H. C., & Han, S. G. (2025). Scaffold biomaterials in the development of cultured meat: A review. *Food Science of Animal Resources, 45*(3), 688–710. https://doi.org/10.5851/kosfa.2025.e13

[7] Marques, D. M. C., Silva, J. C., Serro, A. P., Cabral, J. M. S., Sanjuan-Alberte, P., & Ferreira, F. C. (2022). 3D bioprinting of novel κ-carrageenan bioinks: An algae-derived polysaccharide. *Bioengineering, 9*(3), 109. https://doi.org/10.3390/bioengineering9030109

[8] Chen, Y., Li, L., Chen, L., Shao, W., Chen, X., Fan, X., Liu, Y., Ding, S., Xu, X., Zhou, G., & Feng, X. (2023). Gellan gum-gelatin scaffolds with Ca2+ crosslinking for constructing a structured cell cultured meat model. *Biomaterials, 299*, 122176. https://doi.org/10.1016/j.biomaterials.2023.122176

[9] Hu, X., Tang, H., Wang, J., Su, X., Zou, L., & Xu, B. (2026). Effects of curdlan on 3D-printed meat analogs based on Stropharia rugosoannulata mycelium and pea protein isolate: Printability, rheology, and texture. *Foods, 15*(11),

DOI: 10.54254/2753-8818/2026.ES37304

1971. https://doi.org/10.3390/foods15111971

[10] Kankala, R. K., Zhao, J., Liu, C.-G., Song, X.-J., Yang, D.-Y., Zhu, K., Wang, S.-B., Zhang, Y. S., & Chen, A.-Z. (2019). Highly porous microcarriers for minimally invasive in situ skeletal muscle cell delivery. *Small, 15*, 1901397. https://doi.org/10.1002/smll.201901397

[11] Wang, Y., Zou, L., Liu, W., & Chen, X. (2023). An overview of recent progress in engineering three-dimensional scaffolds for cultured meat production. *Foods (Basel, Switzerland), 12*(13), 2614. https://doi.org/10.3390/foods12132614

[12] Raveendran, D., Dalloul, F., Mietner, J. B., Barba, E., Chen, S., Zaytseva-Zotova, D., Sochor, B., Vayalil, S. K., Müller-Buschbaum, P., Tiainen, H., Roth, S. V., & Navarro, J. R. G. (2025). 3D printable hydrogel based on TEMPO-oxidized cellulose nanofibrils and Fmoc-FF for enhanced biological performance and cell adhesion. *ACS Appl, 8*(38), 18571–18583. https://doi.org/10.1021/acsanm.5c03356

[13] Melzener, L., Spaans, S., Börlin, C. S., Hauck, N., Post, M. J., Doğan, A., & Flack, J. E. (2026). Peptide screening enables optimised biofunctional hydrogels for cultivated meat tissue engineering. *bioRxiv*. https://doi.org/10.64898/2026.05.09.724015