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Current status and prospects of cultured meat research

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Abstract. With the continuous growth of the global population, both the demand for meat and the scale of animal farming have increased sharply, placing immense pressure on the environment. Consequently, the sustainable production of animal-derived protein has become a critical issue. Among various approaches, the technology of cultured meat—producing animal protein in the laboratory from stem cells and other cell types—has emerged as a relatively mature research area. This technique addresses key challenges in traditional animal protein supply through its simple operational process and shorter production cycle. Over decades of development and innovation, cultured meat technology has evolved to include a range of novel methods, such as using xuan paper as a scaffold for cell cultivation, further advancing its potential. This paper provides an overview of cultured meat research, focusing on its background, production processes, three-dimensional culture and tissue shaping techniques, and related commercial developments.

Keywords: cultured meat background, production technology and innovation, three-dimensional culture, tissue shaping

1. Introduction

With the increasing demand for animal-derived protein, large-scale livestock farming has led to significant pollution of water, soil, and air, while traditional animal husbandry also faces persistent food safety issues—all of which pose serious threats to human health [1]. Therefore, there is an urgent need to develop sustainable methods for producing animal protein.

Cell-cultured meat, an emerging approach to sustainable development, enables the production of cell-based products such as meat, eggs, and milk, as well as non-cellular products like proteins and fatty acids, directly from cultivated cells. This approach essentially shifts the main unit of agricultural production from complete living organisms such as plants and animals to cells—the smallest units of life. Cultured meat offers remarkable advantages over conventionally farmed meat in terms of health, safety, and environmental protection [2]. Currently, there are two main production methods for cultured meat: cell engineering and fermentation.

In cell engineering, the primary materials are typically primary cells (stem cells) or genetically modified cell lines. These cells undergo proliferation and differentiation to produce muscle tissue, followed by large-scale expansion of the culture. Finally, food 3D printing technology is used to reconstruct the structure of the cultured meat, forming a compact and elastic three-dimensional texture that simulates the mouthfeel of real meat, thereby enhancing consumer acceptance.

The fermentation approach, on the other hand, relies on recombinant DNA technology to modify microorganisms such as bacteria, algae, and yeast so that they can synthesize animal proteins. This involves inserting genes encoding desired proteins into host cells, cultivating them, and then isolating and purifying the resulting proteins. The microbial strains used in this process are similar to those employed in the production of recombinant proteases.

In 2013, the world's first lab-grown beef hamburger—produced from primary bovine skeletal muscle cells—was created and cooked for public tasting at a press conference in London [3]. Subsequently, U.S. meat companies developed prototype cultured products such as meatballs, beef strips, chicken, and duck. By the end of 2018, Israel announced the successful development of a cultivated beef steak. On November 21, 2019, Professor Zhou Guanghong's team at Nanjing Agricultural University produced China's first muscle stem cell–based cultured meat, using pig muscle stem cells as the source material.

Experts and industry representatives have expressed a range of opinions on this emerging technology. Louise Calderwood, Director of Regulatory Affairs at the American Feed Industry Association (AFIA), noted that while there are no definitive figures showing how much market share conventional meat might lose to plant-based or cell-cultured alternatives, many large corporations have already begun to diversify their operations.

Regarding product safety, Zhong, Deputy Director of the Science Communication Center for Food and Nutrition, stated that since the composition of the culture medium and the cultivation conditions of artificial muscle cells are fully controllable,

cultured meat is theoretically safer than meat from farmed animals.

As for taste and texture, few studies have focused on this aspect specifically. One article briefly noted that the sensory characteristics, nutritional value, and flavor of cell-agriculture products are nearly identical to those of conventional livestock products [1]. With the development of various sensory detection technologies, integrated evaluation methods combining tools such as electronic noses, electronic tongues, GC-MS, and sensory analysis are becoming increasingly widespread. It is reasonable to expect that comprehensive studies on this aspect will emerge in the near future.

The following sections will introduce the production methods of cultured meat, as well as innovations in 3D printing technology and related developments.

2. Production of cultured meat

The production of cultured meat involves extracting seed cells from animal tissue, promoting their proliferation and differentiation through in vitro culture techniques, and processing them using food engineering and tissue engineering technologies. The goal is to create an artificial muscle tissue that closely mimics the microstructure of natural meat.

2.1. Isolation and extraction of seed cells

In the preparation of cultured meat, the isolation and extraction of seed cells play a crucial role. Seed cells refer to cells that can proliferate under in vitro conditions and eventually form muscle tissue. They are typically muscle stem cells or mesenchymal stem cells.

2.1.1. Muscle stem cells

Muscle stem cells are cells with self-renewal capacity and myogenic differentiation potential, and they are one of the primary types of seed cells used in cultured meat production. In this process, muscle stem cells are first isolated from muscle tissue, then expanded and induced to undergo myogenic differentiation in vitro to form mature muscle fibers. These fibers are subsequently processed through food engineering techniques to produce cultured meat.

Muscle stem cells can be obtained by several methods, including enzymatic digestion, tissue explant, and single-fiber isolation [4]. Among these, the enzymatic digestion method is the most commonly used. Fresh muscle tissue is first mechanically minced into a slurry and then digested with protease enzymes to dissociate the tissue and release the cells.

Since muscle stem cell extracts often contain other cell types, the resulting cell suspension must be purified. One purification approach utilizes the low adhesion property of muscle stem cells. The mixed cell suspension is placed on ice for 30 minutes, allowing muscle stem cells to separate from the mixture and settle into the supernatant. The supernatant is then transferred for further culture of muscle stem cells, achieving purification at a relatively low cost [5].

A research team from Jiangnan University [6] further explored the effect of initial purity on the proliferation and myotube formation capacity of porcine muscle stem cells in vitro. By improving the differential adhesion method, they developed a highly efficient and low-cost purification technique. Using this method, approximately 2.1×10^6 muscle stem cells can be obtained per gram of muscle tissue—an output well-suited for the industrial-scale production of cultured meat.

2.1.2. Mesenchymal stem cells

Mesenchymal stem cells (MSCs) are stromal cells with the ability to self-renew and differentiate into multiple lineages. They can be derived from bone marrow, adipose tissue, or umbilical cord, and are accordingly classified as bone marrow-derived MSCs, adipose-derived MSCs, and umbilical cord-derived MSCs. Under laboratory conditions, these cells can be induced to differentiate into various mesodermal lineages, including chondrocytes, osteoblasts, myocytes, and adipocytes, making them ideal seed cells for cultured meat production [7].

The isolation techniques for MSCs vary depending on their tissue source. For example, bone marrow-derived MSCs are usually obtained by aspirating bone marrow fluid followed by purification using density gradient centrifugation [8]. Umbilical cord-derived MSCs, on the other hand, are often isolated through enzymatic digestion or the tissue explant adhesion method. In one study, researchers cut human umbilical cords into 1 mm^2 fragments and cultured them for seven days; spindle-shaped cells emerged around the tissue fragments, successfully yielding umbilical cord MSCs. Moreover, a patent reported an efficient enzymatic digestion method combining collagenase II, hyaluronidase, and calcium chloride solution to process neonatal umbilical cords. From a 2 cm-long segment of umbilical cord, approximately 4.2×10^5 MSCs were isolated. This method effectively digested the Wharton's jelly matrix while maintaining cell viability, significantly shortening the enzymatic digestion time, and allowing stable subculture of the obtained MSCs [9]. Adipose-derived MSCs are particularly suitable as seed cells for

cultured meat due to their abundant and easily accessible sources. Their isolation primarily relies on the enzymatic digestion method [10].

2.2. Development of efficient serum-free culture media

In the industrial production of cultured meat, the culture medium—serving as the source of all essential nutrients—is a critical factor, and its efficiency and cost-effectiveness are of paramount importance. Animal stem cells typically have limited proliferative and differentiation capacities under in vitro conditions, and these abilities tend to decline significantly over time. To address this challenge, it is necessary to gain a deeper understanding of the key regulatory factors and signaling pathways involved in the proliferation, myogenic differentiation, and adipogenic differentiation of different types of stem cells. Such knowledge can facilitate the identification of compounds that effectively promote cell growth, maintain stemness, and regulate cellular functions. These compounds may be derived not only from conventional basal media or fetal bovine serum (FBS), but also through high-throughput screening of natural bioactive compound libraries and small-molecule chemical libraries.

2.2.1. Compounds regulating stem cell proliferation and function

In the field of muscle stem cell research, several studies have identified compounds that promote cell proliferation. For instance, researchers have found that the inexpensive, food-grade small molecule vitamin C can enhance both the proliferation and myogenic differentiation of porcine muscle stem cells in vitro [11]. The maintenance of bovine satellite cells depends on both cell purity and the transmission of the p38 MAPK signaling pathway. By using p38 inhibitors to suppress this pathway, large-scale expansion of primary muscle cells can be achieved [12]. Moreover, insulin-like growth factor-1 (IGF-1) has been shown to increase the expression of cell cycle–related genes, accelerate entry into the S phase, and promote DNA synthesis, thereby enhancing the proliferation rate of chicken embryonic myoblasts. Exogenous IGF-1 can further stimulate myoblast proliferation and promote rapid skeletal muscle growth in vivo [13].

2.2.2. Research on serum substitutes

Fetal bovine serum (FBS) plays a vital role in the growth of animal cells—particularly stem cells—but its use in cultured meat production significantly raises costs and contradicts the ethical goal of avoiding animal slaughter. Therefore, analyzing the components of FBS and developing a chemically defined library of serum substitutes is an essential step toward sustainable production. To date, various components—including hormones, growth factors, and proteins—have been investigated as potential serum replacements [14, 15]. These alternatives aim to provide the necessary nutrients and signaling molecules for cell proliferation and differentiation, while ensuring reproducibility, lower cost, and animal-free production.

2.3. A novel cultivation approach: the potential of Xuan paper in cell culture

In recent years, Xuan paper, a traditional Chinese paper used for calligraphy and painting, has attracted attention as an economical and practical substrate for Three-Dimensional (3D) cell culture due to its unique physical and chemical characteristics. Xuan paper exhibits excellent liquid permeability and a microporous structure, which together create an ideal platform for nutrient diffusion and cell migration during culture.

Xuan paper offers diverse choices in thickness and texture, while remaining relatively inexpensive—making it a promising scaffold material for large-scale applications. Compared with traditional filter paper and lens-cleaning paper, Xuan paper features purer cellulose composition and a finer microcavity network that better supports cell attachment and migration. Furthermore, compared with conventional cell culture microplates, the fibrous structure of Xuan paper provides a larger specific surface area, enhancing cell adhesion and proliferation. Experimental studies have demonstrated that cell proliferation rates on Xuan paper are higher than those on standard filter paper, particularly when using Xuan paper with a thickness of 80 μm [16].

3. Three-Dimensional (3D) culture and tissue shaping

After cell extraction and preliminary cultivation, further 3D culture and tissue shaping are required. This stage represents a critical step in cultured meat production, during which the mass-expanded cells are seeded onto scaffolds and cultured to form structured tissue resembling conventional meat. To date, multiple 3D cell culture and tissue shaping techniques have been developed and applied to cultured meat production. These mainly include traditional solid scaffolds and 3D bioprinting, as well as newer approaches such as electrospinning and microcarrier-based technologies.

3.1. Solid scaffolds

The solid scaffold culture technique involves seeding cells onto a three-dimensional scaffold or mold, where they proliferate and differentiate to form tissues such as muscle fibers and adipose tissue. In this process, hydrogels are commonly used as scaffold materials. Because their structure closely resembles the Extracellular Matrix (ECM), hydrogels facilitate nutrient diffusion essential for cell growth, making them a key factor for successful 3D cell culture. For instance, researchers designed a custom mold [17] in which porcine muscle stem cells were mixed with collagen hydrogel and injected into the mold. Through induction and culture, they successfully obtained a reticular network of porcine muscle tissue. However, hydrogel scaffolds tend to degrade easily and lack sufficient mechanical strength. In contrast, plant protein–based scaffolds possess a more stable, sponge-like structure that provides the necessary mechanical stability to support cell growth and differentiation.

3.2. 3D bioprinting

3D bioprinting utilizes extrusion-based printing to fabricate complex tissue structures by depositing bioinks—mixtures of living cells and non-cellular materials—in a layer-by-layer fashion. After printing, the constructs are cultured to allow cell proliferation, differentiation, and tissue maturation, ultimately forming edible cultured meat. This technique is currently one of the most popular fabrication methods in the food sector. The key to its success lies in the selection of suitable bioinks, which are typically composed of edible polysaccharides and protein polymers such as collagen, gelatin, silk fibroin, fibronectin, and keratin. These materials not only exhibit excellent biocompatibility but also possess rheological and mechanical properties suitable for precise printing. The advantages of 3D bioprinting include the ability to precisely control the shape, pore size, and spatial distribution of both cellular and non-cellular components, as well as to simultaneously print with multiple bioink materials. In recent years, this technology has been successfully applied to cultured meat fabrication. Researchers have noted [18] that proteins, fats, and polysaccharides are the key components determining the texture and structure of food products. Using Whey Protein Isolate (WPI) and Gellan Gum (GG) as bioink materials, they mixed them with muscle stem cells and successfully 3D-printed edible cultured meat constructs.

3.3. Electrospinning

Electrospinning employs an electrostatic field to draw a polymer solution from a syringe needle, forming micro- to nanoscale fibers. Cells are then seeded onto or between these fibers and induced to differentiate into organized tissue. The ultrafine fibers promote cell adhesion, enhance oxygen and nutrient delivery, and provide aligned structures conducive to muscle fiber formation. Studies have demonstrated [19] that electrospun gelatin nanofibers can support the growth of rabbit myoblasts and bovine smooth muscle cells. In this approach, the fibers are first fabricated and subsequently seeded with cells for further cultivation, ultimately forming cultured meat with mechanical and structural properties closely resembling those of natural muscle. Moreover, a bilayer fibrous scaffold made from methacrylated alginate and Polycaprolactone (PCL) has also been shown to support the growth of skeletal muscle cells, leading to the formation of functional muscle tissue.

3.4. Microcarrier technology

Microcarrier technology is a method for producing cultured meat in which cells are inoculated onto edible microcarriers. After proliferation and induced differentiation, the cells form cellular sheets, which are then stacked together to produce cultured meat products. This approach eliminates the need for cell digestion and microcarrier removal, offering significant advantages for industrial-scale production. For example, Park and colleagues developed edible gelatin microspheres using materials such as fish gelatin and cellulose. Under optimal crosslinking conditions, they successfully cultured cell sheets with meat-like properties.

3.5. Latest patent — edible 3D scaffold

A recent patent reveals the development of an edible 3D scaffold composed primarily of chitosan and sodium carboxymethyl cellulose. The scaffold is physically crosslinked using electron-beam irradiation, resulting in a structurally stable framework with excellent cell adhesion and biocompatibility, suitable for culturing skeletal muscle cells. Compared with existing technologies, this invention avoids the use of initiators or catalysts and offers high food safety. Its preparation process is simple, cost-effective, and conducive to large-scale production of structured cultured meat, thereby promoting further progress in this field. In addition, researchers have studied in detail the effects of Carboxymethyl Chitosan (CMCS) on the microstructure, thermal stability, and self-assembly properties of Bovine Bone Collagen (BBC). The introduction of CMCS improves the thermal stability and self-assembly behavior of BBC, providing a useful reference for constructing extracellular matrix analogs for cultured meat based on

collagen and chitosan. This innovation also offers new pathways for the high-value utilization of livestock and poultry bone by-products, creating broader possibilities for developing relatively low-cost cultured beef.

To enable non-destructive, rapid, and accurate food testing, intelligent evaluation instruments—such as electronic noses and electronic tongues—are increasingly being combined with sensory evaluation for food analysis. Currently, such combined methods are widely used in products like chicken soup, Chaozhou-style crispy meatballs, and beef. It is anticipated that in the near future, similar approaches will be developed and applied to the sensory evaluation and intelligent testing of cultured meat, eventually forming a unique evaluation system tailored to this emerging food category.

4. Commercial analysis and conclusion

At the beginning of 2024, the food industry witnessed a landmark event: Israel became the third country in the world to approve cultured meat, following Singapore and the United States. This so-called "food of the future" is now appearing on dinner tables in an increasing number of countries—signaling that the future may already be here. Meat is an essential part of most people's daily diet. If cultured meat could replace even one-tenth of traditional livestock production, its market value could reach trillions of yuan. Currently, over one hundred technology companies worldwide are devoted to advancing cultured meat technologies, striving to make these products indistinguishable from conventional meat in appearance, flavor, nutrition, and price. Perhaps one day, people will enjoy meat without involving animals at all. However, despite the fact that "growing" a piece of meat from a single cell has become a reality, the journey from the laboratory to the dining table remains filled with challenges.

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