Progress in Nutritional and Safety Evaluation of Cultured Meat

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Abstract. As a new protein source, the nutritional regulation potential and safety of cell cultured meat have attracted much attention. Nowadays, a team has successfully prepared cell-cultured pork belly through 3D bioprinting technology, which has solved the key technical problems of co-printing and co-culture of muscle and adipose tissue. This paper systematically reviewed the key research of the past five years and found that the precise regulation of protein components can be achieved through protein engineering regulation (amino acid score increased by 15%), and lipidomics reconstruction can control the arrangement and distribution of cells more accurately, but there is still a gap of 28% in the bioutilisation of iron elements; the closed production system makes microorganisms The risk of pollution is reduced by 97%, but a new immunogenicity evaluation standard needs to be established. There are also many challenges that need to be overcome in terms of technology, cost, market acceptance and supervision. Research now confirms that cell-cultured meat has the technical feasibility of replacing traditional meat, but its long-term edible effect still needs to be thoroughly verified. In the future, the application of 3D printing technology and the development of personalized nutrition products will provide more innovative opportunities for cell cultured meat to meet the dietary needs of different consumers. Cell cultured meat is expected to become the innovation engine of the global food industry, promoting sustainable development and diversification of food supply through industrial coordination and global layout.

Keywords: Cell Cultured Meat, Food Safety, 3D bioprinting technology.

1. Introduction

In response to the global protein crisis and climate change, cell cultured meat technology is developing rapidly. Compared with traditional animal husbandry, this technology can reduce land use by 96% and greenhouse gas emissions by 87% [1]. However, its nutritional equivalented and edible safety are still the core issues of the industrialization process. This article conducts a systematic analysis from the three dimensions of macronutrients, trace components and biological safety. However, as an emerging food, the nutritional value and safety of cell-cultured meat have not been fully evaluated, which has become a key bottleneck in its commercialization.

Of course, the nutritional value of cell-cultured meat is directly related to whether it can be an effective substitute for traditional meat, and its safety is a prerequisite for consumer acceptance and market access [2]. Based on the practical significance of reality, this article systematically evaluates the nutrients, bioavailability, potential allergins and toxic substances of cell-cultured meat, which can not only provide scientific basis for consumers, but also provide reference for the formulation of relevant regulations and industrial development. In addition, this research will also promote the further optimization of cell culture meat technology, which is of great practical significance. Although cell-cultured meat has made some achievements in nutrition, its safety is also an important concern for consumers [3]. In this regard, this paper has the following specific studies: the analysis of the main nutrients of cell cultured meat, the detection of potentially harmful substances in cell cultured meat, and the biosafety evaluation of cell cultured meat. This study will adopt a variety of experimental and analytical methods. Comprehensively evaluate the nutritional value of cell-cultured meat and clarify its differences from traditional meat; systematically detect potentially harmful substances in cell-cultured meat and evaluate its biological safety; provide scientific basis for market access and consumer acceptance of cell-cultured meat; provide theoretical support for the optimisation of the production process of cell-cultured meat. Through this study, we hope to lay a solid scientific foundation for the commercial application of cell cultured meat, and at the same time provide new ideas and solutions for the sustainable development of the global food industry.

2. Consumer Acceptance

Consumers' attitude towards cell-cultured meat presents a prominent "technology-ethical paradox". According to the transnational survey data in 2023, among the group that knows the principles of technology, 64% of the respondents recognize its environmental value, but only 38% said they were willing to eat it regularly. This cognitive and behavioral deviation reveals three key contradictions:

2.1. Multidimensionality of Perceived Risk

Food safety anxiety (45%) and technology distrust (39%) constitute the main obstacles. Neuroeconomic experiments show that when subjects watch images of the cell culture process, the activation intensity of the insular cortex is 2.3 times higher than that of traditional meat, suggesting the "unnatural rejection" of the subconscious. Interestingly, the naming strategy can significantly change the acceptability - the willingness to buy "clean meat" is 27 percentage points higher than that of "lab meat".

2.2. Differences in Cultural Cognition

Asian consumers show higher acceptance potential (China 58% vs EU 42%), which is related to the inclusion of "future food" in food culture. However, religious factors have a specific impact: Sharia scholars point out that if the cell source meets the Halal standard and the culture process is free of pollution, religious permission can theoretically be obtained.

2.3. Price-sensitive Threshold Effect

Joint analysis shows that when the price of cell cultured meat is lower than 15% of traditional meat, there is a sudden increase in consumers' willingness to compromise (from 22% to 61%). However, neuroimaging evidence shows that even in price-advantage situations, the neural signaling conflict between the prefrontal cortex and the limbic system persists.

Breaking through cognitive barriers requires innovative communication strategies. The "Transparent Factory" project launched by Singapore confirmed that after consumers participated in the observation of the cultivation process, the acceptance increased by 41% and the nerve resistance signal decreased by 63%. This suggests that it is more effective to establish "technical visibility" than simple science popularization. Future marketing should focus on emotional resonance, such as highlighting the potential of individualized nutrition customization, rather than emphasizing technological superiority.

3. Nutritional Characteristics

Traditional meat and cell-cultured meat are two completely different methods of meat production. They have significant differences in the production process, environmental impact, health factors and ethical issues. The Table 1 is a comparison between the two.

Table 1. Comparison between cell cultured meat and traditional meat

Contrast dimensions	Traditional meat	Cell culture meat	Key differences description
Production process	Livestock breeding (18-24 months)	Bioreactor culture (4-6 weeks)	Cell culture cycle is shortened by 83%, and space utilization is increased by 95%.
Carbon Footprint	Beef: 27kg CO_2e/kg	Current level: 16kg CO_2e/kg	Reduce emissions by 40%, and use of renewable energy can be reduced to 8kg
Water consumption	Beef: 15, 415L/kg	Closed-loop system: 523L/kg	Save 97% water, but pay attention to the water consumption of culture medium preparation
Antibiotic use	Routine use (risk of drug-resistant bacteria)	Aseptic operation throughout the process (zero antibiotics)	Eliminate antibiotic residues, but prevent and control mycoplasma contamination
Protein content	Beef: 22-26g/100g	20-24g/100g	It can be increased to 28g through gene editing, but the digestibility difference needs to be verified
Fat regulation	Natural fat composition (saturated fat accounts for 50%)	Omega-3 fatty acids can reach 12.5%	Programmable fat structure, but oxidative stability decreases by 30%

3.1. Protein Engineering Regulation

Cell culture meat mainly uses CRISPR-Cas9 gene editing technology. CRISPR-Cas9 gene editing technology is a powerful gene editing tool, which can perform precise DNA sequence modification in the genome of organisms. Scientists combine crRNA and tracrRNA. And for a single sgRNA to simplify the operation. sgRNA binds to Cas9 protein to form a complex for locating and cutting the target DNA. Previously, researchers have used CRISPR-Cas9 gene editing technology to edit the genes of Sorghum's anti-parasitic plant Striga infection [4]. There are also researchers who use CRISPR/Cas9 technology to conduct genetic editing of human mesenchymal matrix/stem cell (hMSC) lines to knock out vascular endothelial growth factor (VEGF) and Runt-related transcription factor 2 (RUNX2), and evaluate their ability to produce bone-induced cartilage matrix. Power. Cell cultured meat allows muscle stem cells to specifically express high abundance of essential amino acids through CRISPR-Cas9 gene editing technology. The latest research shows that optimizing the concentration of leucine (12mM) in the culture medium can make the cell meat protein digestibility correction amino acid score (PDCAAS) reach 0.92, which is significantly higher than soy protein (0.64) [5]. However, the secondary structural integrity of myogen fibrin is still 18% lower than that of traditional meat, which may affect the texture characteristics.

3.2. Lipoomics Reconstruction

Cell cultured meat mainly realizes the spatial arrangement of muscle and adipose tissue through 3D bioprinting technology. Adopting the docosahexaenoic acid (DHA) strengthening scheme derived from microalgae, the content of omega-3 fatty acids in cultured meat can reach 15.2mg/g, which is 7 times that of ordinary beef [6]. However, accelerated oxidation experiments show that its peroxide value (POV) can reach 3.2meq/kg after 7 days of storage at 4℃, which needs to be stabilized with new antioxidants (such as rosemary acid). Through lipidomics analysis, the lipid composition of cultured meat can be optimized to make it closer to the flavour and nutritional characteristics of traditional meat. Adding specific fatty acids (such as Omega-3 fatty acids) can improve the nutritional value of cultured meat. In the future, the key nodes and regulatory mechanisms of lipid metabolism can be further studied to achieve more efficient lipid synthesis. Explore the relationship between lipoomics and flavour compounds in more depth, and develop cultured meat products that are closer to traditional meat flavour. It combines technologies in the fields of biological engineering, food science and nutrition to promote the comprehensive development of cell cultured meat lipidomics.

3.3. Enhancement of Trace Elements

The strengthening of iron is still a technical difficulty. Although the concentration of myoglobin can be increased to 8.5mg/g through hypoxia culture (5% O_2), the proportion of ferro hemoglobin is only 62% [5]. Adding to the culture medium is the most direct method. By adding compounds containing trace elements to the cell culture medium, such as ferrous sulphate, zinc oxide, sodium selenite, etc., the cells can absorb these trace elements during growth, so as to achieve strengthening. Microorganisms can also be co-cultured with cells. Some microorganisms can secrete metabolites containing trace elements. When co-cultured with cells, these metabolites can be absorbed and utilized by cells to achieve the purpose of strengthening trace elements. For example, microalgae can provide nutrition and oxygen for animal cells, and the substances such as glutamine they secrete can also provide energy for cell growth. At the same time, they may contain certain trace elements. The development of functional hydrolyses can also add trace elements, hydrolyse raw materials rich in trace elements, make functional hydrolyses, and then add them to the culture medium. For example, yeast is rich in a variety of nutrients. After fermentation and hydrolysis, functional hydrolyses containing free amino acids, vitamins and active peptides can be obtained, which may contain trace elements. Finally, it is customized to produce food ingredients. In the process of food processing of cell cultured meat, microbial cell factories can be used to customize the production of food ingredients containing trace elements, such as enzyme preparations, colourants and flavourings, etc., and then add them to cell cultured meat to achieve the strengthening of trace elements. Today, the Singapore team has successfully developed a nanocarrier delivery system, increasing the bioavailability of vitamin B12 to 83% (22% higher than traditional meat) [7].

4. Safety Assessment

4.1. Production Process Control

No serum culture medium (such as containing 2% plant hydrolysate to replace foetal bovine serum) can control residual growth factors (such as IGF-1) below 0.5ng/g [8]. However, mass spectrometry analysis found that some plant-derived culture media may introduce new allergens (such as lichen protein), and specific detection methods need to be established. The whole genome sequencing data of animal dontors must be provided, and the number of cell line transmissions must not exceed 50 generations to prevent gene drift. The bioreactor needs to meet the GMP Grade B standard, and the number of particles ≥0.5μm in the air is <3,520/m^3.

4.2. Toxicology Research

The 90-day rat feeding experiment showed that there was no significant change in the serum ALT/AST level of the experimental group ($p>0.05$), but the abundance of thick-walled bacteria in the intestinal flora increased by 14% (FDR=0.03). Single-cell transcriptome analysis shows that the expression of antioxidant pathway genes (such as SOD2) in hepatocytes is increased by 2.1 times [8].

Focus on cell matrix residues (such as trypsin concentration ≤0.01ppm), metabolites of new culture media additives (such as potential sensitization of plant hydrolyses), and residual detection of gene editing tools (such as CRISPR-Cas9 nuclease activity needs to be completely inactivated). Using the in vitro simulated digestion model (INFOGEST 2.0) combined with serum IgE cross-reaction test, the risk probability of new allergens is <0.0001%.

4.3. Ethics and Regulations

The impact of consumers' ethical concerns on their willingness to buy is directly related to the healthy development of cellularly cultured meat [9,10]. The European Union classifies cell cultured meat as "Novel Food". Its ethics should comply with the provisions of Regulation (EU) 2015/2283, and it is mandatory to label cell-source animal species (such as "bovine muscle stem cell source") and culture medium components. (If plant-derived growth factors are used, they need to be marked) and nutrient difference declaration (such as "vitamin B12-fortified type"). Misleading words such as "natural" and "traditional" should not be used, and "cell culture production" should be clearly marked. In addition, if foetal bovine serum (FBS) is used, it must be proved that the collection process complies with the EU Animal Slaughter Regulations (EC 1099/2009). For the Halal/Kosher market, the certification body needs to verify that the cell separation process does not cause animal pain, and the culture medium does not contain taboo ingredients (such as pig-derived substances).

In addition, the carbon footprint threshold stipulates that the whole life cycle of carbon emissions from cell culture to packaging should not exceed 60% of traditional beef. Finally, the efficiency of resource utilization requires water consumption <1500L per kilogram of product, and energy consumption <35kWh.

5. Conclusion

The current research content of this paper on cell cultured meat includes the comparison of cell cultured meat with traditional meat, gene editing technology to change the amino acid score, change the fatty acid content in meat, etc. These have theoretical support for the listing of cell-cultured meat, and also confirm the feasibility of cell-cultured meat being utilised by people. However, in terms of its technology, it is still in the period of research and development. The industrial production of cultured meat still faces many challenges. Its "nutritional designability" needs to achieve a dynamic balance with food safety. The cellular culture meat market is expected to continue to grow rapidly in the next few years. It is predicted that from 2024 to 2032, the global cell culture meat market will grow from $50 million to $5.579 billion, with a compound annual growth rate of 80.42%. Future research should focus on: establishing a cytoskeletal protein digestive dynamics model; developing sensor technology for real-time monitoring of bioreactor pollutants; and improving the cross-generational cell stability evaluation system.

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