The Sustainable Development Issues of Animal Cell-cultured Meat

Wanting Xu [1], Jinkai Yang [2, *] and Zhe Yu [3]

[1] School of Nursing and Health Management, Shanghai University of Medicine & Health Sciences, Shanghai, 200120, China

[2] School of Food Science and Technology, Jiangnan University, Wuxi, 214122, China

[3] School of Food Science, Guangdong Pharmaceutical University, Zhongshan City, 528400, China

* Corresponding Author Email: 1012220332@stu.jiangnan.edu.cn

Abstract. As an innovative technology for alternative protein production, cell-cultured meat faces various sustainability challenges in terms of environment, economy and society. This paper systematically reviews its production processes (including cell acquisition and selection, scale production, cell differentiation and tissue formation) Analyses show that this technology can significantly reduce land use, water consumption and carbon emissions compared to traditional stock farming. In terms of economy, the high cost of culture mediums and equipment restricts the commercialization process, leading to the fact that its production is highly dependent on technological innovation and large-scale production to achieve cost reduction and efficiency increase. Social acceptance is divided and consumers are increasingly concerned about food safety and ethics. Public awareness needs to be enhanced through transparent communication and policy guidance. Research shows that cell-cultured meat has the potential to alleviate food crisis and ecological stress, but its sustainable development path needs to be coordinated with technological breakthroughs, cost optimization and social acceptance.

Keywords: Cell-cultured meat, sustainability, production process, resource consumption, economy.

1. Introduction

With the expansion of the global population, the traditional stock farming will face more severe tests and stress from resources, environment and the public. As one of the most important components of human diet, meat has contributed to the abundant market demand. According to the forecast of the World Food and Agriculture Organization, the world demand for meat will increase by 70 percent to 455 million tons by 2050 [1]. Therefore, as a new food biosynthesis technology emerging in recent years [2], the emergence and development of cell-cultured meat technology can not only relieve the pressure on meat supply, but also reduce the demand for land and water resources in livestock industry. Besides, more dietary options are offered to people in the future.

According to the Food and Agriculture Organization of the United Nations, livestock contributes about 14.5 percent of global greenhouse gas emissions and occupies 30 percent of ice-free land area [3]. Westhoek pointed out that the pollution treatment cost caused by pork farming is a major driving factor of environmental pressure [4]. In addition to the environmental climate change and increasing public concerns about food security, animal cell-cultured meat has been regarded as one of the most potential alternatives that can subvert traditional stock farming. Its development has also been highly concerned by academia, industry and other fields.

Although cell-cultured meat technology shows sufficient research potential, its development still faces many sustainability challenges. For instance, fetal bovine serum (FBS) is currently considered as one of the widely applied additives for in vitro cell culture. Its production costs a lot and improper screening of serum will lead to a lot of human and material resources waste [5]. In addition, the large-scale production of bioreactors also poses a huge challenge to energy consumption. Zhao pointed out that the overall cognition level of Chinese residents regarding cell-cultured meat is rather low. Consumers with a high cognition level only accounted for 31.87 percent of the research group [6].

Therefore, consumers' cognition level and acceptance of cell-cultured meat are potential problems for the sustainable development of cell-cultured meat in the future.

The purpose of this study is to analyze the sustainable development of the cell-cultured meat industry, including cell selection, culture medium and bioreactor optimization, combined with social economy and consumer awareness factors. The study also explores the impact of cost control, consumer acceptance and related policies on its future development to identify key difficulties.

2. Production Process and Technical Challenges of Cell-cultured Meat

2.1. Cell Aquisition and Selection

Muscle stem cells, including animal embryonic stem cells, adult stem cells and fibroblasts, need to be extracted from live animals such as cows, chickens and pigs as seed cells for production of cell-cultured meat [7]. From a sustainability perspective, obtaining cells through non-invasive biopsies can reduce dependence on animals and thus reduce animal welfare issues in traditional livestock farming. The Dutch company Mosa Meat, for example, could theoretically reduce animal use by 99 percent by taking cells from a single biopsy and expanding them indefinitely [8].

2.2. Cell Culture and Mass Production

The nutrients required for the growth and proliferation of the obtained seed cells in vitro depend on the medium. Amino acids, sugars, vitamins, minerals and growth factors are usually added to the medium. Then the bioreactor is further used to control the temperature, air, pH and other factors in the petri dish to achieve large-scale expansion of cells. The addition of sufficient nutrients in the medium is also conductive to the proliferation and differentiation of cells, and help the final product show the characteristics of traditional meat [9]. A stirred reactor is usually used in the process, but the energy consumption and waste emissions still need to be optimized. Israeli company Future Meat, for example, has developed a perfusion reactor that reduces culture-medium consumption by 30 percent.

2.3. Cell Differentiation and Tissue Formation

After culture, the collected cells are inoculated into the corresponding edible scaffold, and the culture conditions (mechanical stimulation, electrical stimulation, growth factor gradient, etc.) are regulated to differentiate stem cells into muscle fibers and fats. Scaffold material (collagen, cellulose, alginate, etc.) is the source of some of the protein in the cultured meat, which can build a 3D scaffold that stimulates the structure and texture of real muscle tissue, helping to form the final edible tissue. However, the differentiation of cells capable of adipogenic differentiation produces cultured meat fat products with fatty acids and flavor compositions similar to those of animal fats [10].

In terms of sustainability innovations, plastic pollution can be avoided by using biodegradable materials such as alginate or plant fibers as scaffolds, while by-products of the culture solution such as lactic acid can be recycled for the production of biofuels, thus achieving resource recycling [11].

3. Environmental Sustainability Problems

3.1. Use of Land

Animal cell cultured meat, as an emerging method of meat production, has a significant impact on land use problem, mainly manifested in the following aspects:

3.1.1. Remarkable Reduce Land Occupation

Traditional livestock farming requires a large amount of land for grazing and growing feed crops, which imposes a huge pressure on land resources. However, the production process of cell-cultured meat is completed entirely in laboratories or factories, without occupying a large amount of land.

Studies have shown that the land usage of cell-cultured meat can be reduced by 98% compared to traditional meat production, and some research even indicates that its land usage can be reduced by 99%. This means that cell-cultured meat can meet the demand for meat without relying on land resources, thereby releasing a large amount of land that was originally used for livestock farming for other ecological or agricultural purposes [12-14].

3.1.2. Mitigate Land Degradation and Ecological Pressure

The excessive use of land by traditional livestock farming often leads to land degradation, soil erosion, and ecosystem damage. The production method of cell-cultured meat avoids these problems because it does not rely on land resources, thereby reducing the negative impact on the ecological environment. In addition, cell-cultured meat can also reduce greenhouse gas emissions caused by livestock farming and lower the impact on global climate change [12, 13, 15].

3.1.3. Improve the Efficiency of Resource Utilization

The production process of cell-cultured meat directly produces meat from the cellular level, avoiding the waste of energy and resources during the growth of animals in traditional livestock farming. Through precise control of the production process, cell-cultured meat can more efficiently utilize resources and reduce the consumption of land, water, and energy.

3.1.4. Sustainable Utilization of Land Resources

The promotion of cell-cultured meat contributes to the sustainable utilization of land resources. With the global population growth and the increase in meat demand, the pressure on land from traditional livestock farming will continue to increase. Cell-cultured meat, as an alternative solution, can meet the demand for meat without increasing the burden on land, while providing support for food security and ecological protection. Table 1 below shows the comparison of land occupation between traditional livestock farming and cell-cultured meat [12].

Table 1. Comparison of Some Indicators Regarding Land Occupation between Traditional Livestock Farming and Cultured Meat from Cells

lndex	Traditional Animal Husbandry	Cell-cultured Meat
Land Usage Volume	It occupies approximately 70% of the global agricultural land, including 26% of the ice-free land area used for grazing, and 33% of the farmland used for growing feed.	99% less than traditional livestock farming
Land Use Efficiency	The utilization efficiency of land resources is low. A large amount of land is used for grazing and feed cultivation.	Significantly enhance land utilization efficiency without the need for large-scale grazing or feed cultivation
Impact on the Ecological Environment	Resulting in deforestation, land degradation and ecosystem destruction	Reduce land occupation and lower the pressure on the ecosystem.
Potential Environmental Improvement	Without any obvious improvement measures, a large amount of land resources continues to be occupied.	If fully adopted, it could make 1/4 of the world's land available for reforestation.

3.2. Water Resources

Animal cell cultured meat has significant advantages in water resource utilization, mainly reflected in the following aspects:

3.2.1. Markedly Decreasing Water Consumption

Compared with traditional livestock farming, the production process of cell cultured meat requires a substantial reduction in water consumption. Traditional livestock farming demands a large amount of water in the stages of feed cultivation, livestock breeding, and slaughter processing, while the production of cell cultured meat is mainly carried out in laboratories or factories, without the need for feed crop cultivation and livestock breeding. Therefore, it can significantly save water resources. Studies have shown that the production of cell cultured meat can reduce water consumption by 82% - 96% [16].

3.2.2. Decreasing water pollution

Traditional livestock farming is one of the main sources of water pollution. Livestock manure and wastewater generated during feed processing have caused severe pollution to water bodies. In contrast, the production process of cell cultured meat is highly controllable and does not generate a large amount of wastewater, thereby reducing pollution to the water environment. The following Table 2 is a comparison of some indicators in terms of water resources between traditional livestock farming and cell cultured meat [13].

Table 2. Comparison of some indicators regarding water resources between traditional livestock farming and cultured meat produced through cell cultivation

Index	Traditional Animal Husbandry	Cell-cultured Meat
Proportion of Water Resources Occupation	Accounting for approximately 15% of the total global water consumption	Reduce by 82% to 96% compared with traditional livestock farming.
The Amount of Water Used for Producing 1 Kilogram of Meat	Beef: Approximately 15,000 liters	Beef: Approximately 600 liters
Production Efficiency	The efficiency of water resource utilization is low and there is a phenomenon of waste.	The efficiency of water resource utilization is high and there is almost no waste.
Environmental Impact	The water used for raw material production, livestock drinking and cleaning etc. has caused water pollution.	A closed production environment, generating almost no pollution.

3.2.3. Sustainable Utilization of Water Resources

The production mode of cell-cultured meat has further enhanced the efficiency of water resource utilization by optimizing the composition of the culture medium and the production process. Moreove3r, with the continuous advancement of technology, cell-cultured meat is expected to achieve more efficient water resource recycling in the future, thereby reducing its reliance on fresh water resources.

3.2.4. Technical Challenges and Future Improvement Directions

Although cell-cultured meat has significant advantages in water resource utilization, its production process still requires a certain amount of water resources for the preparation of the culture medium and other production stages. In the future, through the development of more efficient culture medium formulations, optimization of production processes, and the introduction of sustainable water resource management technologies, cell-cultured meat is expected to further reduce water resource consumption.

3.3. Greenhouse Gas Emissions

Animal cell-cultured meat, as an emerging meat production method, has various impacts on greenhouse gas emissions, mainly depending on production technologies and energy sources. These impacts are mainly reflected in the following aspects [15-18]:

3.3.1. Potential Environmental Advantages of Cell-Cultured Meat

Cell-cultured meat theoretically has significant environmental advantages. Compared with traditional livestock farming, the production process of cell-cultured meat does not require large-scale feed cultivation, animal breeding, and slaughtering, thus significantly reducing land use, water resource consumption, and greenhouse gas emissions. Some studies estimate that cell-cultured meat can reduce 78% - 96% of greenhouse gas emissions and significantly reduce land and water resource usage. The following Table 3 shows the comparison of some indicators in terms of carbon emissions between traditional livestock farming and cell-cultured meat [12-13].

Table 3. Comparison of Some Indicators Regarding Carbon Emissions between Traditional Livestock Farming and Cultured Meat by Cell Culture Method

Index	Traditional Animal Husbandry	Cell-cultured Meat
Carbon Emission	The global livestock industry contributes to 15% of human carbon emissions. Among them, beef production emits approximately 60-100 kilograms of CO_2 equivalent per kilogram.	Depending on the production method: If food-grade media and clean energy are used, the emission per kilogram of cell-cultured meat is 10-75 kilograms of CO_2; if highly purified biopharmaceutical-grade media is used, the emission per kilogram could be as high as 246-1508 kilograms of CO_2.
The Main Sources of Emissions	Feed production (45%), animal intestinal fermentation (39%), manure management, land use change	Energy consumption of bioreactors and production of culture media
Emission Reduction Capacity	Optimize the feed formula, enhance the breeding efficiency and reduce the fecal discharge.	Utilize renewable energy sources, optimize the composition of the culture medium, and enhance production efficiency.
The Overall Impact on the Environment	It occupies a large amount of land and water resources, and causes significant damage to the ecosystem.	Significantly reduce the use of land and water resources and lower the pressure on the ecosystem.

3.3.2. Challenges of Current Production Technology

However, the latest research also indicates that the production process of cell-cultured meat may encounter significant carbon emission issues. For instance, a study conducted by the University of California, Davis found that the current production technology of cell-cultured meat may contribute to global warming at a potential rate of 4 to 25 times that of traditional beef. The main reasons include:

Firstly, the high-energy-consuming purification of nutrient solutions. The production of cell-cultured meat requires high-purity nutrient solutions, and the preparation process involves high-energy-consuming techniques such as ultrafiltration and chromatography, which significantly increase carbon emissions. Secondly, energy-intensive bioreactors: The cell-cultured process requires continuous energy supply to maintain the operation of bioreactors, which may involve the use of fossil fuels.

3.3.3. Future Improvement Directions

Despite the challenges of current technology, significant reductions in the carbon footprint of cell-cultured meat can be achieved through the following approaches:

Firstly, optimize production processes: reduce reliance on high-purity growth media and shift to more sustainable raw material sources. Secondly, utilize renewable energy sources, such as solar and wind energy, to power production facilities, thereby reducing reliance on fossil fuels. Additionally, in terms of technological innovation, develop more efficient cell-culturing technologies and equipment to lower energy consumption during the production process.

3.4. Biodiversity

Animal cell cultured meat, as an emerging meat production technology, mainly affects biodiversity in the following aspects:

3.4.1. Reducing Damage to Natural Ecosystems

Traditional livestock farming requires a large amount of land for grazing and feed cultivation, which leads to deforestation, habitat destruction, and the loss of biodiversity. In contrast, the production process of cell-cultured meat is carried out entirely in laboratories or factories, without occupying a large amount of land, thereby reducing damage to natural ecosystems [14,16,19].

3.4.2. Reducing Greenhouse Gas Emissions

Traditional livestock farming is one of the main sources of greenhouse gas emissions, accounting for 18% of global total emissions, with methane emissions accounting for up to 37%. The production process of cell-cultured meat can significantly reduce greenhouse gas emissions and mitigate the impact on climate change. This not only helps protect biodiversity but also alleviates the degradation of ecosystems caused by climate change.

3.4.3. Reducing water and energy consumption

The production process of cell-cultured meat is more efficient than that of traditional livestock farming, significantly reducing water and energy usage. For example, cell-cultured meat can reduce 78% - 96% of greenhouse gas emissions, 99% of land use, and 82% - 96% of water consumption. This efficient resource utilization approach helps protect water resources and energy, and reduces the impact on ecosystems. Table 4 below shows the comparison of some indicators in terms of biodiversity between traditional livestock farming and cell-cultured meat [14].

Table 4. Comparison of some indicators regarding biodiversity between traditional livestock farming and cultured meat produced through cell cultivation

Index	Traditional Animal Husbandry	Cell-cultured Meat
Habitat Destruction	Resulting in deforestation and fragmentation of habitats, it poses a threat to the survival of wild animals and plants.	There is no need for large-scale grazing or feed cultivation, and the destruction of habitats can be reduced.
Species Diversity	Pastoralism and feed crop cultivation have led to a decline in biodiversity, especially in terms of soil microorganisms and plant diversity.	Does not involve grazing and feed cultivation, and has a relatively minor impact on biodiversity.
Ecosystem Service	Deforestation and land degradation reduce ecosystem services such as carbon sequestration and water conservation.	By reducing land occupation, indirect protection of ecosystem services can be achieved.

3.4.4. Reducing the Risk of Zoonotic Diseases

In traditional livestock farming, the transmission of diseases between animals and humans is a significant issue, such as avian influenza and swine flu. The production process of cell-cultured meat is carried out entirely in a sterile environment, avoiding the risk of zoonotic diseases and thereby reducing the indirect impact on biodiversity caused by disease transmission [15].

3.4.5. Promoting the Diversification of Sustainable Protein Sources

The development of cell-cultured meat technology provides humans with a more sustainable source of protein, helping to reduce reliance on traditional livestock farming. This technology can not only meet human demand for meat but also reduce biodiversity loss caused by excessive livestock farming [20-21].

3.4.6. Potential Contribution to Biodiversity Conservation

The promotion of cultured meat from cells can liberate a large amount of land that was originally used for livestock farming. These lands can then be utilized for ecological restoration, forest protection or the establishment of nature reserves. Moreover, reducing the pressure on land and water resources caused by livestock farming also helps to protect the habitats of endangered species.

4. Economic Sustainability and Social Ethics

4.1. High Costs

In its early stages, the development of cell-cultured meat faces numerous technical challenges (e.g., maintaining stem cell pluripotency, developing culture media, scaling up seed cell production, and advancing food processing technologies), leading to high production costs and elevated market prices [22].

A major obstacle to the commercialization of cell-cultured meat is consumer concern over its high cost. In 2013, scientist Mark Post successfully created the world's first cell-cultured beef burger at a cost of approximately $325,000, with a per-kilogram price of around $2.3 million. Even with 2019 technology, the production cost of cultured meat remained over $400,000 per kilogram [23].

4.2. Sustainable Development

A review of existing literature [24] reveals that some studies, based on consumer behavior theory and welfare economics, have utilized nationwide consumer survey data to construct a generalized ordered Logit model. This model provides an in-depth analysis of Chinese consumers' willingness to pay (WTP) for cultured meat and its influencing factors, further supplemented by marginal effect analysis and heterogeneity analysis. Additionally, the contingent valuation method (CVM) was employed to estimate consumers' WTP for cultured meat through interval regression modeling, comparing differences across demographic groups and examining the impact of external information on WTP. The findings indicate:

(1) Consumers' WTP for cultured meat is significantly influenced by age, education level, awareness of cultured meat, and the proportion of household spending on groceries. Specifically, younger consumers, those with higher education levels, and those with greater knowledge of cultured meat exhibit a higher WTP.

(2) Household consumption expenditure and income level have a significant positive impact on WTP. Consumers with higher food expenditure ratios and higher incomes are more inclined to purchase cultured meat.

(3) Dietary habits and food safety perceptions also significantly affect WTP. Consumers who dine out frequently, have higher acceptance of food technology, are concerned about food sustainability, and are more tolerant of food safety risks show stronger purchasing intentions.

(4) The average WTP for cultured meat among consumers is ¥10.475 per *jin* (approximately 500 grams), with a median WTP of ¥7.678 per *jin*. Significant variations exist across different demographic groups, and external information interventions can also notably influence WTP.

In summary, consumers' WTP for cultured meat is shaped by a combination of factors, including personal characteristics, economic conditions, dietary habits, and food safety perceptions. These findings offer valuable insights for market promotion and policy formulation regarding cultured meat.

Moreover, the development of cultured meat may conflict with consumers' perception of food "naturalness." While meat production methods have evolved, consumer attitudes may not shift simultaneously. Traditionally, the taste and nutritional value of meat have been closely associated with natural animal growth and their environment. However, cultured meat, produced through industrial methods, lacks these natural attributes and is entirely detached from traditional farming environments. Despite being a technological innovation, its absence of conventional livestock characteristics may raise skepticism among consumers, affecting acceptance.

Currently, cultured meat still struggles to fully replicate the sensory qualities—such as texture and flavor—of conventional meat, which may lead to an "unnatural" eating experience. Recent survey data shows that approximately 52% of respondents are willing to try cultured meat, while 22% explicitly reject it, and 26% remain undecided. This suggests that while cultured meat holds market potential, its sensory limitations remain a key barrier to consumer acceptance.

4.3. Legal Regulations and Oversight

The sustainable development of the cultured meat industry is closely tied to public perception and consumer willingness. Despite its technological promise, concerns regarding safety and ethics remain contentious [25].

Currently, an international regulatory framework for cultured meat is gradually taking shape, with policies addressing key production inputs (e.g., cell lines, culture media, scaffolds) and potential food safety risks (see Table 5). For instance, the Singapore Food Agency mandates that cell lines must be free from infectious agents (e.g., viruses, bacteria, fungi, prions), and biopsy tissues must be screened for animal diseases. The European Union emphasizes accurate cell identity verification and transparency in sourcing. Given the complexity of culture media, strict control during production is prioritized globally. For scaffold materials, regulatory bodies focus on allergenicity, edibility, and risk assessment of metabolic byproducts. Additionally, genetic stability during cell cultivation is a key regulatory concern. Post-market, labeling must clearly distinguish cultured meat from conventional products to prevent consumer confusion. Overall, beyond standard food safety risks (e.g., allergens, pathogens, chemical hazards), cultured meat regulation particularly emphasizes cell line safety, media and scaffold composition, and genetic stability [10].

Although China has made continuous breakthroughs in the production technology and research and development of cell-based meat, there is relatively insufficient research and discussion on legal norms and regulatory systems [26].

Table 5. Comparative Analysis of Relevant Legislative Norms on Cultured Meat Production in Europe, America and Singapore

Region	Regulations	Content
European Union	"Consumer Food Information Regulations"	New types of food need to be specially labeled to describe information such as the source, ingredients or expected consumption conditions of the food, in order to ensure that the general public, especially young and vulnerable consumer groups, fully understand the nature and safety of the new food.
America	/	The first legal regulation on the labels of cultured meat cells was promulgated in Missouri, the United States. More than 20 states including South Dakota and New Mexico have successively enacted legislation to restrict the labeling of cultured meat cells as "meat". The North American Meat Institute and the Meat Poultry and Seafood Innovation Alliance jointly sent a letter to the United States Department of Agriculture, demanding that mandatory labels be affixed to cultured meat cells.
Singapore	"New Requirements for Food Safety Assessment"	1. Description of the entire manufacturing process and the characteristics of cultured meat products 2. Information related to the cell lines and culture media used 3. Information about the scaffold materials (if any are used) 4. Information on how to preserve the purity and genetic stability of cell cultures during the manufacturing process 5. Safety assessment, covering potential hazards during the production of cultured meat 6. Other safety evaluations, such as digestibility determination, allergen analysis, gene sequencing, etc.

Currently, China has yet to establish clear regulatory policies or guidelines specifically for cultured meat. However, by examining the regulatory frameworks of other countries, China's approach can be further refined and updated [27].

Enhancing the flavor and quality of cultured meat is crucial for its commercialization. At present, most cultured meat products consist of a single cell type and scaffold, resulting in a relatively simple composition that still falls short of the complex tissue structure and rich flavor profile of conventional meat. Therefore, future research should focus on developing cultured meat products incorporating multiple cell types and components, while optimizing taste and texture through the addition of natural flavor compounds. As an emerging technology that do not require slaughter and have the potential for sustainable development, cell-cultured meat is poised to overcome existing challenges through technological breakthroughs, ultimately making its way to dining tables worldwide [2].

5. Conclusion

The sustainable potential of animal cell-cultured meat as an alternative to traditional livestock farming presents a complex situation on multiple fronts. From a technical point of view, although the technological breakthroughs in cell acquisition, large-scale culture and tissue construction have made remarkable progress, the efficiency of bioreactors, the cost of serum-free culture medium and the precise control of the three-dimensional structure of muscle tissue are still the main technical bottlenecks in their large-scale production. In terms of environmental sustainability, cultured meat has theoretical advantages over traditional livestock farming in terms of land use efficiency, water resource consumption and greenhouse gas emissions, but the current production system's high dependence on clean energy and the environmental footprint of culture-medium raw materials still need to be achieved through technological innovation. On the economic level, despite the downward trend of production costs, the price parity with traditional meat still relies on production system optimization and supply chain reconstruction. Meanwhile, consumers' cognitive bias, lack of cultural identity and ethical disputes on "laboratory meat" constitute deep obstacles to market promotion. Future research needs to build a multidisciplinary collaborative innovation system, focusing on breaking through key technologies such as cell metabolism regulation and low-cost culture medium development, and coordinate the relationship between scientific and technological innovation, policies, regulations and social acceptability through participatory governance model, so as to finally realize the collaborative development of cell-cultured meat in four dimensions: technical feasibility, environmental friendliness, economic competitiveness and social acceptability.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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