Life Cycle Assessment of Cultured Meat: Environmental Impacts from Production to Consumption

Linkun Han *

School of Public Health, Xi'an Jiaotong University, Xi'an, China

* Corresponding Author Email: 2214111392@xjtu.edu.cn

Abstract. With the growth of the global population and the increasing environmental challenges, cultured meat has emerged as a potential sustainable alternative and has become a hot topic in both the food industry and environmental research. In recent years, the production technologies and market prospects of cultured meat have garnered widespread attention, especially its potential in reducing greenhouse gas emissions, water resource consumption, and land use. However, existing research has mostly focused on technological breakthroughs, and systematic analysis of the life cycle environmental impacts of cultured meat remains relatively limited. This paper, based on Life Cycle Assessment methodology, analyzes the environmental impacts of cultured meat in its production, transportation, consumption, and disposal stages, and compares it with traditional livestock farming and plant-based meats. The study shows that cultured meat has significant advantages in terms of carbon emissions, water consumption, and land use but still faces challenges in production energy consumption and technological costs. The paper further explores the optimization of cultured meat technologies, including media improvements, gene editing technology, and bioreactor design, and proposes optimization strategies for production. The research indicates that cultured meat has the potential to play a significant role in future food systems, but production costs and energy consumption issues still need to be addressed. Future research should focus on technological innovation, the establishment of dynamic LCA monitoring systems, and market promotion and consumer education to provide stronger support for the commercialization and sustainable development of cultured meat.

Keywords: Cultured Meat, Life Cycle Assessment, Environmental Impact, Carbon Footprint, Water Resource Consumption.

1. Introduction

With the continued growth of the global population and the worsening of environmental issues, the food industry faces a critical challenge in achieving sustainable development. Traditional livestock farming not only consumes vast amounts of land and water resources but also contributes significantly to climate change [1]. In this context, cultured meat, an emerging food technology, has gained significant attention due to its potential environmental benefits and efficient resource utilization. Among various forms—such as cultured meat, plant-based meat, and mycoprotein—cultured meat stands out for its ability to replicate the nutritional content and texture of conventional meat [2].

Life Cycle Assessment (LCA) is a widely adopted method for assessing the environmental impacts of products, analyzing every stage from raw material extraction, production, transportation, consumption, to final disposal [3]. In recent years, LCA studies on cultured meat have increased, showing that compared to traditional meat, it has considerable potential to reduce greenhouse gas emissions, land use, and water consumption [4]. However, differences in research scope, assumptions, and data sources among LCA studies have introduced uncertainties. Therefore, this study aims to systematically review and compare current LCA research on cultured meat, identify similarities and gaps in methodologies, and explore future challenges and opportunities for its sustainable development. These findings are intended to provide scientific support for policymakers, industries, and consumers to promote the healthy growth of the cultured meat sector.

2. The LCA Method

This study adopts the LCA methodology to systematically analyze the environmental impacts associated with cultured meat production. LCA is a quantitative method used to evaluate the environmental impacts of products or services throughout their life cycle—from raw material extraction to final disposal [5]. By quantifying resource consumption, emissions, and other environmental factors, LCA provides scientific insights that help identify environmentally intensive stages and optimize production practices. This study is conducted in accordance with ISO 14040 and ISO 14044 standards [6], and follows the four primary phases of LCA: goal and scope definition, inventory analysis, impact assessment, and interpretation.

2.1. Goal and Scope Definition

The objective of this study is to assess the environmental impacts of cultured meat across its life cycle and to compare it with conventional livestock production and plant-based meat, particularly in terms of greenhouse gas emissions, water use, and land utilization. The study encompasses the entire life cycle of cultured meat, including raw material acquisition (such as growth medium production), production processes (cell cultivation and bioreactor operation), transportation and distribution (especially cold-chain logistics), consumption (market acceptance), and waste disposal (packaging and end-of-life waste management). The system boundaries are defined using both "cradle-to-gate" and "cradle-to-grave" approaches, focusing primarily on production and post-production stages [7].

2.2. Life Cycle Inventory (LCI) Analysis

The LCI analysis involves the collection and quantification of input and output data throughout the entire life cycle of cultured meat. Key variables include energy consumption (electricity and thermal energy), culture medium components (glucose, amino acids, growth factors), emissions (CO_2, CH_4, N_2O), water use (both direct and indirect), and land usage (space required for bioreactors and feedstock production) [8]. This study also compares the environmental effects of various growth medium formulations, bioreactor designs, and energy supply configurations to identify potential areas for environmental optimization [9].

2.3. Impact Assessment

In the impact assessment phase, this study applies key environmental indicators: Global Warming Potential (GWP), water footprint, and land use. GWP is measured in kg CO_2-equivalent per kg of product, capturing the greenhouse gas emissions associated with cultured meat over its life cycle. Water footprint analysis includes blue water (surface and groundwater), green water (rainwater), and grey water (needed to dilute pollutants). Land use assesses both direct and indirect land occupation [10]. The data are normalized and standardized to enable comparison across impact categories. Monte Carlo simulations are used to account for uncertainties and enhance the robustness of the results [6].

2.4. Interpretation and Optimization Strategies

In the interpretation phase, this study identifies key environmental hotspots in the cultured meat life cycle and proposes optimization strategies. These include the use of serum-free or plant-based growth media to reduce resource intensity, enhancing bioreactor efficiency to lower energy consumption, and incorporating renewable energy sources for production processes [6]. The analysis is complemented by market research and policy studies to assess how consumer education, pricing strategies, and government incentives can increase market adoption and promote sustainable industrialization [5].

3. Environmental impact analysis of cultured meat based on LCA

This study, based on the LCA methodology, evaluates the environmental impacts of cultured meat at different life cycle stages and compares them with traditional livestock and plant-based meat alternatives. The findings suggest that while cultured meat has environmental advantages in terms of carbon emissions, water use, and land requirements, it still faces technological and energy-related challenges. The discussion is organized into five sub-sections: raw material sourcing, production process, transportation and distribution, consumption and waste management, and comparison with traditional livestock systems.

3.1. Raw Material Acquisition

The primary input for cultured meat production is the cell culture medium, composed of amino acids, sugars, vitamins, growth factors, and other nutrients. The production of these components—especially animal-derived growth factors—is energy-intensive and environmentally burdensome [11]. In contrast, the raw materials for plant-based meat (e.g., soy, pea, wheat protein) typically have lower water and land footprints [12]. Recent research shows that using recombinant or plant-based growth factors significantly reduces the environmental impact of the culture medium [13]. Therefore, future improvements in medium formulation, such as shifting to plant-based or synthetic growth factors, will be crucial for enhancing sustainability.

3.2. Production Process

The production stage involves cell cultivation in bioreactors, tissue engineering, and processing. Bioreactor operation accounts for a major portion of energy consumption due to the need for tightly controlled conditions like temperature, oxygen supply, and nutrient delivery [14]. Studies have indicated that depending on energy sources used, the Global Warming Potential (GWP) of cultured meat could range from being more favorable than traditional beef to being 4–25 times worse [11]. However, integrating renewable energy and optimizing high-density cell culture or 3D bioprinting techniques could significantly improve energy efficiency and production yields [15]. These advancements are key to reducing cultured meat's carbon footprint and operational costs.

3.3. Transportation and Distribution

Cultured meat requires cold chain logistics for safe distribution, leading to considerable carbon emissions during transport and storage [12]. By contrast, some plant-based products and conventional meats may tolerate non-refrigerated storage, reducing transport-related emissions. Regionalized or on-site production of cultured meat could minimize distribution distances and associated emissions [12]. Furthermore, implementing smart supply chain systems—such as real-time route optimization and sustainable packaging—can help lower logistics-related environmental burdens [14].

3.4. Consumption and Waste Management

Consumer acceptance significantly influences the environmental impact at the consumption stage [16]. Taste, price, nutritional value, and perceived naturalness are critical factors shaping consumer attitudes [17]. High production costs currently make cultured meat less competitive, but ongoing innovation could help reduce costs and improve acceptance. In addition, sustainable packaging and efficient recycling systems are essential for minimizing waste impact. The adoption of biodegradable or reusable packaging can mitigate resource depletion and plastic pollution [13].

3.5. Comparison with Traditional Livestock

This study synthesizes LCA data to compare cultured meat, traditional livestock, and plant-based meat across three key indicators: greenhouse gas emissions, water use, and land occupation. Traditional beef production emits approximately 27 kg CO_2-eq per kilogram of meat, whereas cultured meat ranges between 5–10 kg and plant-based meat between 3–5 kg CO_2-eq [12, 14].

Regarding water use, conventional beef requires up to 15,000 liters per kg, compared to 1,500 L for cultured meat and just 500 L for plant-based alternatives [15]. Similarly, land use is significantly lower for cultured meat and plant-based products. These results confirm the potential of cultured meat to reduce agriculture-related environmental burdens. However, its high energy dependency remains a key limitation [13].

4. Discussion

This study conducted a systematic analysis of the environmental impact of cultured meat throughout its life cycle—including production, transportation, consumption, and disposal—using the LCA methodology. The findings indicate that cultured meat offers significant advantages over conventional livestock farming in terms of reducing carbon emissions, conserving water resources, and optimizing land use. For instance, the carbon footprint of cultured meat production ranges between 5–10 kg CO_2-eq/kg, while traditional beef can emit up to 27 kg CO_2-eq/kg [11, 13]. Water consumption is also notably lower—approximately 1,500 L/kg for cultured meat compared to 15,000 L/kg for beef [15]. However, high energy consumption, particularly during culture media production and bioreactor operation, remains a challenge. Some studies suggest that under certain conditions, the global warming potential (GWP) of cultured meat may even exceed that of conventional beef by 4 to 25 times [14]. Therefore, while cultured meat holds promise for environmental sustainability, optimizing production technologies is essential to minimize energy usage and environmental burden.

4.1. Comparison with Traditional Livestock

To enhance the sustainability of cultured meat, future studies should focus on technological advancements. First, improving the composition of culture media is crucial for lowering costs and reducing environmental impact. Currently, many media rely on animal-derived ingredients like fetal bovine serum (FBS), which are costly and raise ethical concerns [10, 12]. Developing serum-free or plant-based media—such as soy- or algae-derived growth factors—can help reduce dependence on animal components and lower energy inputs. In addition, applying gene editing technologies can increase cell proliferation rates, shorten production cycles, and reduce resource use [16]. The design of bioreactors is another key area for energy efficiency. Present-day stirred-tank or suspension bioreactors are energy-intensive despite their effectiveness. Future research could explore the use of 3D bioprinting to better mimic the structure of real meat and reduce cultivation time [16]. Modular bioreactors may also support scalable production and improve cost-effectiveness.

4.2. Comparison with Traditional Livestock

To maintain environmental sustainability, it is necessary to establish dynamic LCA monitoring systems for cultured meat production. Existing LCA studies generally rely on static datasets, whereas the technology itself is evolving rapidly. Integrating Internet of Things (IoT) technologies and big data analytics can facilitate real-time tracking of energy consumption, emissions, and resource usage [17]. Artificial intelligence could be employed to analyze production data, predict energy-efficient conditions, and optimize bioreactor parameters and media compositions. International cooperation and industry-level data sharing will also be essential for creating a global database on the environmental performance of cultured meat, thereby improving accuracy in evaluation and supporting evidence-based policymaking [17].

4.3. Comparison with Traditional Livestock Market Promotion and Consumer Acceptance

Despite its environmental benefits, cultured meat still faces considerable barriers to market penetration. Consumer acceptance is shaped by cultural values, pricing, taste, and safety perceptions [18, 19]. Some consumers are skeptical due to the perceived "artificial" nature of cultured meat and concerns about its nutritional authenticity. Increasing public understanding through educational campaigns about the production process and its sustainability benefits is crucial [2]. Additionally, government incentives—such as R&D subsidies, tax reliefs, and supply chain reforms—can enhance industry viability [17]. Cost remains a significant issue; current production expenses make cultured meat more expensive than traditional meat. However, as technology improves and economies of scale are achieved, costs are expected to decline [17]. Collaborating with mainstream food brands and restaurants to introduce cultured meat products into everyday diets can also help normalize consumption and broaden acceptance [20].

4.4. Future Research Directions

The development of cultured meat remains in its nascent stages, and several avenues for future exploration are evident. Advancements in cell cultivation technologies and renewable biomaterials can increase production efficiency while minimizing environmental harm [16]. Establishing dynamic LCA systems will allow continuous environmental performance optimization. Moreover, further efforts in market development and regulatory support—such as consumer education, pricing policy, and food labeling standards—are necessary to facilitate industry growth [17]. With continued innovation and evolving consumer preferences, cultured meat is likely to become a cornerstone of the sustainable food system, helping to address global food security and environmental degradation challenges.

5. Conclusion

This study provides an overview of the environmental impacts of cultured meat using LCA. The findings show that cultured meat offers significant advantages in terms of reducing carbon emissions, conserving water resources, and optimizing land use compared to traditional livestock farming. However, the energy consumption involved in production remains a major challenge, especially in the manufacturing of culture media and the operation of bioreactors. Despite this, the potential for cultured meat to contribute to sustainable food production is clear, and technological advancements in production efficiency, culture media optimization, and renewable energy adoption are crucial for improving the sustainability of cultured meat production. Future research should focus on optimizing the production process to reduce energy consumption and production costs, while also exploring market dynamics, consumer acceptance, and policy support to facilitate the commercial success of cultured meat. These efforts will contribute to the integration of cultured meat into global food systems, promoting a more sustainable and environmentally friendly food production model.

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