Future Foods 13 (2026) 100984

Contents lists available at ScienceDirect

Future Foods

journal homepage: www.elsevier.com/locate/fufo

Cultivated meat for sustainable food security and environmental resilience

Yu-Chien Lin [a,b], Naiem Ahmad Wani [a,b], Idan Yakir [a,b,f], Xue Wei Liu [b,c], Assaf Friedler [b,d], Mattan Hurevich [b,d], Weibiao Zhou [b,e], Zvi Hayouka [b,f], Steve Oh [b], Shlomo Yitzchaik [b,d], Nam-Joon Cho [a,b,g,*]

[a] School of Materials Science and Engineering, Nanyang Technological University, 50 Nanyang Drive, 637553, Singapore
[b] Singapore-HUJ Alliance for Research and Enterprise, Singapore HUJ Alliance Research Enterprise (SHARE) 1 CREATE Way, #03-09 Innovation Wing, 138602, Singapore
[c] School of Chemistry, Chemical Engineering and Biotechnology, Nanyang Technological University, 21 Nanyang Link, Singapore, 637371, Singapore
[d] The Institute of Chemistry, The Hebrew University of Jerusalem, 9190401 Israel
[e] Department of Food Science & Technology, Office: S14-05-01National University of Singapore 3 Science Drive 3 Singapore 117543, Singapore
[f] Institute of Biochemistry, Food Science and Nutrition, Robert H. Smith Faculty of Agriculture, Food and Environment, The Hebrew University of Jerusalem, Herzl 229, Rehovot 7610001, Israel
[g] Centre for Cross Economy Global, Nanyang Technological University, Singapore

ARTICLE INFO

Keywords:
Cellular agriculture
Cultivated meat
Alternative food
Food safety
Infection control
AI-assisted bioprocessing

ABSTRACT

Cultivated meat (CM) is an emerging field of research that applies cell-culture and bioprocessing technologies to the production of animal-derived food products without conventional animal farming. Growing global demand for meat, coupled with environmental and resource constraints associated with existing production systems, has motivated increasing academic, industrial, and policy interest in CM. Beyond its research and commercial implications, CM has the potential to contribute to social stability and food security, particularly in regions with limited arable land and high dependence on food imports, and may reduce vulnerability to global disruptions such as zoonotic disease outbreaks (e.g., avian influenza). This review offers a comprehensive analysis of the field, addressing the growing demand for CM, technical advancements, and the challenges in translating CM production into scalable applications. It examines current technological obstacles, highlights recent research progress, and explores potential solutions for achieving sustainable growth in the industry. By evaluating the intricacies of CM, this review aims to provide insights into the strategies needed to advance this innovative field and meet future demands for sustainable and secure food sources.

1. Introduction

The expanding field of cultivated meat (CM) reflects a global response to the growing limitations of conventional livestock farming. Traditional animal agriculture, while long essential to global nutrition and rural livelihoods, faces increasing scrutiny due to its substantial environmental, ethical, and public-health burdens (Ferrari, 2025). Livestock production is estimated to contribute approximately 14 – 18 % of anthropogenic greenhouse-gas (GHG) emissions and to occupy nearly 70 % of global agricultural land (Piantino et al., 2025). However, recent analyses emphasize that such aggregated indicators are highly dependent on system boundaries and land classification, as a substantial proportion of land used by livestock consists of grasslands unsuitable for crop production and therefore does not directly compete with human food cultivation (Mottet et al., 2017; Peyraud & Hocquette, 2025). Accordingly, environmental and land-use impacts of livestock systems should be interpreted with caution, accounting for land quality, opportunity cost, and regional production context rather than absolute area alone. Water-use estimates for ruminant production have similarly been subject to reinterpretation. While ruminant systems have previously been reported to require up to 15,000 L of water per kilogram (kg) of beef based on volume-based water footprint assessments (Lim et al., 2025) , subsequent analyses indicate that these values largely reflect the aggregation of rainfall-driven evapotranspiration (green water), surface and groundwater withdrawals (blue water), and water required to dilute pollutants (grey water). As emphasized by (Peyraud et al., 2025) , impact-oriented assessments focusing on blue-water consumption and local water stress yield substantially lower and more context-dependent

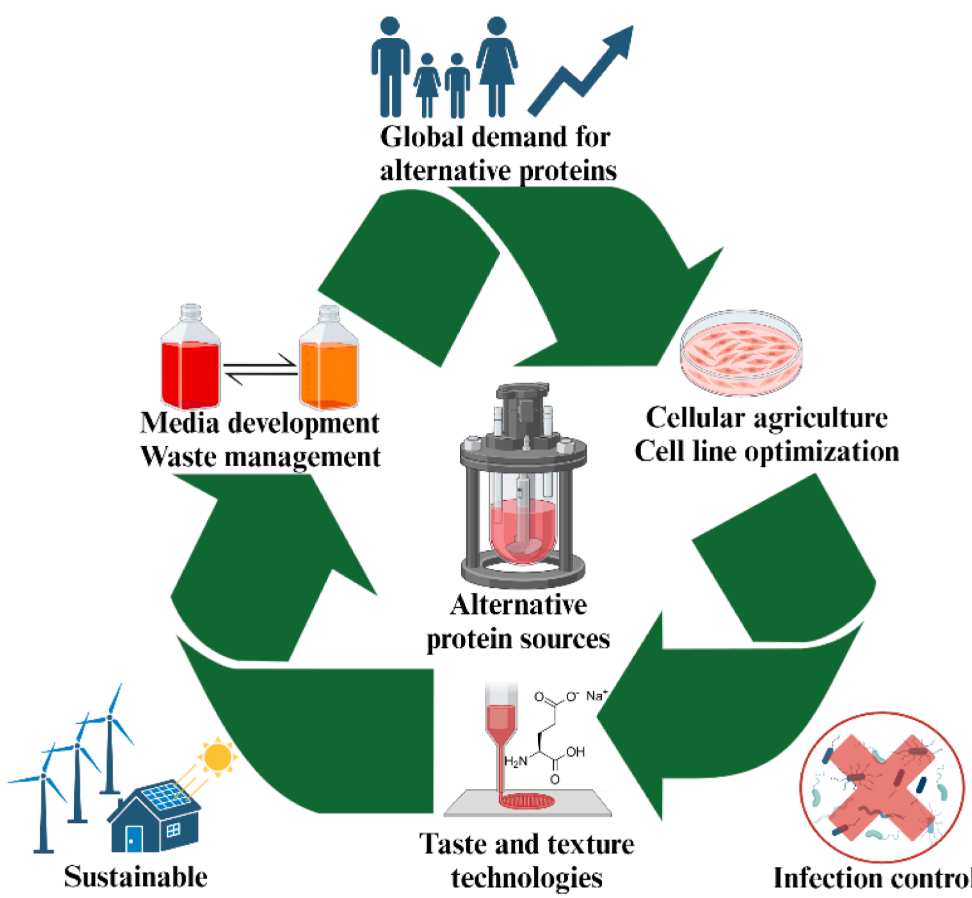
* Corresponding author at: School of Materials Science and Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore.
E-mail address: njcho@ntu.edu.sg (N.-J. Cho).

https://doi.org/10.1016/j.fufo.2026.100984
Received 9 July 2025; Received in revised form 17 December 2025; Accepted 8 March 2026
Available online 9 March 2026

estimates, and therefore do not necessarily reflect direct competition for freshwater resources. Beyond land and water considerations, ruminant production typically exhibits relatively low feed-to-protein conversion efficiency, averaging approximately 6 – 10 kg of feed per kg of meat produced. In addition, intensive livestock systems often rely on antibiotics and growth-promoting agents, which have been associated with antimicrobial resistance and zoonotic disease risks, while carcass processing may introduce further microbial and chemical contamination concerns (Castellani et al., 2025). The CM industry has seen significant progress over recent years, driven by the need to address the concerns associated with traditional animal agriculture. CM offers a solution to long-standing animal-welfare concerns and underscores the urgency for alternative protein systems capable of decoupling meat supply from conventional animal farming. Within this context, CM has been proposed as a biotechnology-driven approach that seeks to cultivate animal cells directly in an effort to reproduce selected sensory and nutritional attributes of meat, while potentially reducing ecological impacts and animal suffering. (Dvash & Lavon, 2024).

Despite the considerable momentum in research and development, evident by the involvement of approximately 200 companies fervently pursuing the creation of CM products, the path to widespread adoption and commercialization of these novel alternative food sources remains riddled with formidable challenges (Cai et al., 2024). While technological advancements have been pivotal in the development of CM enabling precise cell culture, improved bioreactor design, and edible scaffold materials. However, consumer acceptance remains the decisive factor determining the trajectory of this emerging industry. As (J.-F. Hocquette et al., 2025) highlighted, the perception of CM as an artificial or unnatural food creates social and ethical resistance that may outweigh technical barriers. Likewise, (Wood et al., 2023) reported that most consumers express curiosity rather than long-term willingness to purchase, often citing uncertainty about safety, nutrition, and authenticity. Ultimately, the success of CM depends on building public trust and demonstrating tangible benefits ethical, environmental, and sensory that justify its inclusion in mainstream diets. High acceptance will, in turn, drive further investment and technological innovation, creating a virtuous cycle where market demand fuels research progress, and reliable, cost-effective technology reinforces consumer confidence (A. C. A. Santos et al., 2023). However, the industry faces challenges such as high production costs, scalability issues, and regulatory barriers that need to be addressed to achieve commercial viability (Kirsch et al., 2023).

This review is structured thematically, with each section addressing a distinct aspect of the CM landscape: (i) technological foundations and production processes; (ii) environmental and sustainability implications; (iii) food security and socio-economic considerations; (iv) policy and regulatory frameworks; (v) public perception and consumer acceptance; and (vi) future directions and innovation strategies. Using evidence from scholarship, market analysis, and policy review, this paper exposes CM's commercial and social hurdles and argues that cross-disciplinary partnerships and continued innovation are essential to realize its promise for a resilient, equitable, and sustainable food system. To support this goal, the review adopts a narrative synthesis approach, integrating insights from a wide range of peer-reviewed publications, industry reports, and regulatory documents. By thematically organizing the discussion across technological, environmental, economic, and policy domains, the review identifies current knowledge gaps, evaluates



Schematics. Conceptual illustration of cultivated meat (CM) as one of several alternative protein approaches aimed at addressing global protein demand. The scheme outlines key research and development components within the CM production system, including cell line optimization, contamination risk control, modulation of flavor and texture, sustainability considerations, and circular resource utilization such as culture media recycling. These elements collectively represent critical technical and system-level factors under investigation in the broader development of alternative protein production.

potential impacts, and highlights opportunities to accelerate the integration of CM into the global food supply chain.

Schematics.

2. Societal drivers and consumer acceptance of cultivated meat

A stable food supply is the cornerstone of social stability, especially for countries like Singapore, which lack arable land. CM is not only a matter of research and commerce but also a relevant consideration within broader food resilience and security frameworks. Moreover, even countries with vast territories like China and India still rely on food imports. During the recent COVID-19 pandemic, food shortages highlighted the vulnerability of global supply chains, and future zoonotic outbreaks, such as avian influenza, could pose similar risks (Wells et al., 2023). According to a report by the U.S. Centers for Disease Control and Prevention, since January 20, 2022, over 12,000 wild birds have been confirmed to be infected with H5N1, and more than 162 million poultry have been affected by outbreaks. The virus has also been detected in 973 dairy herds across 16 U.S. states. Although rare, transmission to mammals has been observed, particularly in species that were in close contact with infected birds, indicating a potential for zoonotic transmission. Therefore, CM could contribute to enhancing food security and resilience as part of a diversified and sustainable food system.

These crises have underscored the importance of improving food production efficiency, reducing food waste, and enhancing local self-sufficiency (Coucke et al., 2023). To pre-emptively address potential disruptions caused by future pandemics, fostering localized and resource-efficient food production including innovative protein sources such as CM will be essential (González-Monroy et al., 2021). Meat and milk from cattle provide approximately 45 % of the global protein supply, yet about 86 % of livestock protein (in skin, wool, bone, and organs) remains inedible for humans (Mottet et al., 2017). This subsection examines the critical social and behavioral factors influencing consumer acceptance of CM and highlights the need to improve its perceived taste, naturalness, familiarity, and environmental impact (Fidder & Graça, 2023). Insights from global health crises underscore the importance of understanding and influencing consumer behavior (Güney & Sangün, 2021). However, surveys consistently show that CM is less appealing to consumers than traditional or plant-based meat (Coucke et al., 2023), with reasons ranging from health concerns and religious beliefs to entrenched dietary habits, rather than simple food neophobia (Krings et al., 2022). Similarly, a large-scale French study reported that most consumers still perceive CM as unnatural, unappetizing, and potentially harmful, showing lower levels of trust in laboratories and start-ups, with acceptance largely limited to younger and highly educated groups (É. Hocquette et al., 2022). Improving public understanding through transparent communication about CM's production process and benefits has been shown to enhance consumer acceptance. Table 1 summarizes surveys from various studies regarding the perceptions and concerns of people in different regions about accepting CM. Interestingly, there is a greater willingness to try CM in Eastern countries compared to Western nations (Liu, Hocquette et al., 2021). Based on Table 1, consumer acceptance of CM remains moderate, with a consistent set of priorities emerging. Price is the most critical factor most consumers are unwilling to pay more than for conventional meat, followed by taste and texture, safety and naturalness, and trust in production transparency. While younger, educated, and environmentally conscious individuals show greater openness, older consumers and those in the meat industry remain skeptical. Overall, despite awareness of ethical and environmental benefits, economic feasibility and sensory authenticity remain the strongest determinants of global consumer acceptance.

Table 1
Summarizes the perceptions and acceptance levels of consumer surveys regarding cultivated meat in various countries around the world.

No	Focus	Region of Study	Key Findings	Reference
1	Consumer perceptions and acceptance for commercialization	Various (Global Review)	Consumer acceptance of cultivated meat remains mixed, influenced by factors such as safety, naturalness, taste, and price. The authors highlight that public communication, transparent labeling, and policy support will be crucial to improve trust and accelerate adoption.	(Samad et al., 2024)
2	Factors influencing cultivated meat acceptance	Various (Global Review)	Identified key factors affecting acceptance, such as environmental benefits, health concerns, ethical considerations, and sensory attributes (taste, texture). Consumers who were more environmentally conscious and concerned about animal welfare showed higher acceptance of cultivated meat.	(Pakseresht, Kaliji, & Canavari, 2022)
3	Preferences for plant-based, hybrid, and cultivated meat	Belgium	Found that consumer preferences varied by meal context and consumption moment. Cultivated meat was generally preferred over hybrid and plant-based alternatives when offered in familiar meal contexts and when consumers were made aware of cultivated meat 's ethical and environmental benefits.	(Coucke et al., 2023)
4	How social and policy factors shape its commercialization.	Various (Global Review)	Consumer attitudes toward cultivated meat are strongly influenced by cultural values, perceived naturalness, safety, and price, while clear regulatory frameworks and public communication	(Bui, Filimonau, & Ermolaev, 2025)

(continued on next page)

Table 1 (*continued*)

No	Focus	Region of Study	Key Findings	Reference
			are identified as essential for improving acceptance and building long-term trust.	
5	US and UK consumer segmentation on cultivated meat	USA, UK	Identified distinct consumer segments with varying levels of acceptance. "Early adopters" showed a high willingness to try and purchase cultivated meat, while "skeptics" were more concerned about unnaturalness and safety. Educational initiatives focusing on health and environmental benefits could shift skeptical consumers towards acceptance.	(Szejda, Bryant, & Urbanovich, 2021)
6	Rural vs. urban consumer attitudes towards cultivated meat	Ireland	Urban consumers accepted cultivated meat more than their rural counterparts, mainly due to greater exposure to new food technologies and higher concern for environmental sustainability. Rural consumers were more skeptical, concerned about taste and the "unnatural" aspect of cultivated meat.	(Shaw & Mac Con Iomaire, 2019)
7	Attitudes of Australian Gen Z towards cultivated meat	Australia	Found that Generation Z in Australia is generally open to the idea of cultivated meat, particularly due to environmental and ethical concerns. However, concerns about taste, texture, and potential health impacts were noted as barriers to wider acceptance.	(Bogueva & Marinova, 2020)
8	How consumer perceptions, social identity, and political values shape the acceptance of cultivated meat	USA	Consumer acceptance of cultivated meat was mainly influenced by three factors: (I) its appearance and taste, as people valued how closely it resembled conventional meat; (II) their personal and political beliefs, such as views on consumer freedom and government regulation; and (III) the level of communication and transparency, where clear, evidence-based information was key to building trust and acceptance.	(Gerber, Bae, Ramirez, & Cash, 2025)
9	Comparison of cultivated meat acceptance in Germany and France	Germany, France	Germans showed a higher level of acceptance compared to the French, largely due to stronger environmental concerns and a greater familiarity with food innovations. French consumers were more skeptical, with concerns about the taste, safety, and the perceived "unnaturalness" of cultivated meat.	(Bryant, van Nek, & Rolland, 2020)
10	How consumers willing to try, willing to regularly eat, and willing to pay	Italy, Portugal, and Spain	Among 2,171 participants, 65.5 % were willing to try and 56.7 % to regularly eat cultivated meat, but only 5.7 % would pay more than for conventional meat. Younger people, scientists, and non-meat-industry workers showed higher acceptance, driven by perceptions of CM as ethical, eco-friendly, and healthy, while cost, emotional resistance, and safety or taste concerns remained key barriers.	(Liu et al., 2023)
11	Perceptions of its societal promise, ethical/ environmental framing, and	Germany	Among 3,558 German consumers, 70 % were willing to try and 57 % to	(Jacobs, Windhorst, Gickel, Chriki, Hocquette, &

(continued on next page)

Table 1 (*continued*)

No	Focus	Region of Study	Key Findings	Reference
	demographic influences on acceptance.		regularly eat artificial meat, though most preferred paying the same as conventional meat. Acceptance was higher among younger, educated, and low-meat-consuming groups, driven by ethical and environmental motives, while cost and regulatory concerns limited broader adoption.	Ellies-Oury, 2024)
12	How familiarity, trust, and perceived naturalness influence willingness to adopt cultivated meat.	France	The study surveyed 5,418 French consumers and found that while awareness of cultivated meat remains low, acceptance is hindered by concerns over artificiality, safety, health risks, and price, emphasizing that trust, transparency, and clear communication are essential to improve consumer confidence.	(Gousset et al., 2022)
13	Examining psychological and social drivers behind willingness to try or reject the product	France	A survey of 5,718 French consumers revealed that while 40–50 % acknowledged ethical and environmental issues in livestock farming, only 18–26 % believed cultured meat could address them. Most perceived it as unnatural, unhealthy, or disgusting, with just 23.9 % finding it “interesting” and 16.9 % calling it “promising.” Over 91 % were unwilling to pay more than for conventional meat. Young people and women showed greater openness, whereas older men and meat professionals were most resistant, indicating that cultured meat in France is likely to remain a niche product with limited impact.	(É. Hocquette et al., 2022)
14	How technical, ethical, cultural, and social dimensions intersect with sensory, nutritional, and environmental expectations	Various (Global Review)	The study emphasizes that consumer acceptance of cell-based foods depends on balancing intrinsic and extrinsic quality attributes while addressing major gaps in scalability, cost-effective animal-free media, and regulatory understanding, with trust, transparency, and culturally sensitive communication being essential for global legitimacy and adoption.	(Chriki et al., 2025)
15	How education, income, and familiarity influence willingness to try and adopt the product.	Brazil (São Paulo and Salvador)	Among 809 participants from São Paulo showed greater awareness and acceptance of cultivated meat than those from Salvador. Familiarity strongly correlated with willingness to try, while rejection was mainly driven by food neophobia, perceived artificiality, and health concerns. The authors emphasize that communication, education, and policy strategies must be region-specific to effectively improve public acceptance across diverse populations.	(Mendes, Biscarra-Bellio, Heidemann, Taconeli, & Molento, 2025)
16	Qualitative analysis of knowledge, perceptions, and acceptance of cultivated meat	Chinese	The study found that while Chinese consumers generally recognize the environmental and ethical benefits of cultured meat, their acceptance is limited by low	(Pareti et al., 2025)

(continued on next page)

Table 1 (*continued*)

No	Focus	Region of Study	Key Findings	Reference
			awareness, concerns over taste authenticity, cost, and safety, making legislative support, technological improvement, and transparent traceability essential to build long-term trust.	

3. Key innovations and challenges in scaling up sustainable cellular agriculture

Safe and stable upscaling of CM is crucial for two main reasons: 1) to ensure a continuous and controllable supply of cells for the creation and development of CM products, and 2) to enable large-scale market penetration that allows consumers to integrate CM seamlessly into mainstream diets alongside conventional food sources. Beyond bioreactor engineering, recent international frameworks emphasize that scale-up must advance in parallel with a robust, risk-based safety governance system. The Food and Agriculture Organization (FAO) stakeholder roundtable (Mukherjee et al., 2025) consolidated a four-phase hazard-identification framework covering cell selection, production, harvesting, and food processing and emphasized HACCP-, GMP-, and GHP-style food safety plans focusing on novel or specific inputs (e.g., media components, novel equipment) that may not exist in conventional foods (Powell et al., 2025). Building on this, previous study (Bennie et al., 2025) proposes a risk-based cell line and cell banking architecture including Master/Working Cell Banks, standardized identity and contamination testing, and dossier components aligned with existing biomedical/bioprocessing playbooks to control hazards from the bank-up through scale-up. Such standardized cell-banking systems are also critical to mitigate the risk of genetic drift identified by FAO and to ensure genetic stability across production batches(Organization, 2023). Moreover, by establishing well-characterized and immortalized cell lines, companies can reduce reliance on repeated muscle biopsies from live animals, improving both reproducibility and ethical compliance. These sources jointly highlight that quality control and safety assurance must be standardized for food-grade cell banks and scaled manufacturing, with regulators drawing from neighbouring fields while adapting tests to food-safe use cases.

Complementing these institutional perspectives, (Chriki et al., 2022) highlight ethical, semantic, and nutritional uncertainties that remain unresolved even if manufacturing hurdles are overcome. They argue that referring to cultured tissue as “meat” may be semantically and legally contentious, since the term “meat” in many jurisdictions refers specifically to edible tissues derived directly from slaughtered animals. In line with this reasoning, FAO prefers the term “cell-based food” rather than “meat” in its official guidance documents, emphasizing that this terminology more accurately reflects the underlying production process (i.e., cell cultivation) and helps distinguish such products from conventional slaughtered animal products. The FAO/WHO report (Organization, 2023) explicitly frames “cell-based food” as food items produced by culturing cells isolated from animals excluding the broader use of “meat” to reduce ambiguity in regulatory, safety, and labeling contexts.

Extending this debate, (Chriki et al., 2025) underscore that CM must fulfill both intrinsic (safety, nutrition, sensory) and extrinsic (ethics, environmental impact, cultural acceptance) quality expectations. They identify animal-free and recyclable culture media as a critical sustainability bottleneck, while cautioning that many of CM’s purported environmental benefits remain model-based and unverified at industrial scale. By examining these critical elements, we provide a comprehensive view of the technical state-of-the-art and the safety systems needed to realize industrial-scale production. Four main elements are identified and will be discussed in dedicated subsections(Singh & Kumar, 2025): (i) cell line development and banking, (ii) media and inputs control (including recycling/reuse), (iii) bioreactor scale-up and contamination prevention, and (iv) post-harvest processing and product safety documentation.

3.1. Continuous or immortal cell line development

Establishing a continuous or immortal cell line with rapid doubling times is a pivotal milestone in scaling up cell production in CM. The source of these cells from diverse animal species is imperative, requiring properties that allow continuous growth over hundreds of generations, accompanied by short doubling times of preferably below 24 hours (Pajčin et al., 2022). These cells can be derived from early tissues of young animals, spontaneously immortalized in culture, or transformed into a pluripotent stem cell stage to promote cell mass expansion (Reiss et al., 2021). Table 2 summarizes a range of cell types from mammalian and avian species that have been published, but there is a paucity of reference to seafood cell lines. While noteworthy strides have been made by various companies, including Upsides Food, Good Meat, Mosa Meat, and Aleph Farms, in deriving extended cultures of avian, porcine, and bovine cell types (Pasitka et al., 2023), challenges persist in establishing continuous lines from vital fish species such as tuna, mackerel, and salmon, as well as crustaceans like prawns, lobsters, and crabs, owing to historical limitations in basic research and characterization under lab cell culture conditions (Saad et al., 2023). This section explores current and emerging technologies that enhance the biological aspects of cell cultivation, ensuring a sustainable and economically viable foundation for CM production. Heavily engineered cell lines may face stricter regulatory hurdles to ensure their safety to consumers, and the high opportunity cost may hinder adoption. By exploring various methodologies for generating cell lines, this review draws on insights from relevant literature to critically evaluate the efficiency of cell cultivation technologies, shedding light on challenges and potential solutions in this critical aspect of CM (Goswami et al., 2022).

3.2. Development of bioprocesses to achieve high cell density

Developing bioprocesses capable of achieving high cell densities is fundamental for ensuring an efficient rate of cell production in the context of CM (Allan et al., 2019). Typical 2D culture processes face challenges such as low growth rates, metabolic inefficiency, and catabolite inhibition. Thus, cell density is very difficult to increase from 10^4 to 10^5 cells/cm^2 (Rowley et al., 2012). Additionally, the choice of cells is also very important to achieve high cell density. The output weight per unit volume varies greatly depending on cell size. Smaller cells can achieve higher maximum cell concentrations while consuming a similar medium (Hellung-Larsen & Andersen, 1989). Three-dimensional (3D) suspension cultures like packed bed bioreactor and microcarriers can be used to achieve higher cell density to 10^7 to 10^8 cells/mL by increasing nutrient and O_2 exchange (Lembong et al., 2020). Current industry targets aim to achieve 25 to 50 g/L of cell mass, recognizing that smaller cells, such as those of prawns, will weigh significantly less when compared to larger fibroblasts. A comparative benchmark in the biotherapeutics field reveals that Chinese Hamster Ovary (CHO) cells have attained densities of 6×10^7 cells/ml to 1.2×10^8 cells/mL in perfusion cultures (Table 2) (Schwarz et al., 2023). Recent advancements in suspension chicken cell lines have also achieved exceptionally high cell densities in culture, although the literature on similar yields in intensive cultures for other cell lines remains limited (Pasitka et al., 2023). It is possible to provide higher growth density by designing microcarrier properties, such as their morphology, tensile

Table 2
Summary of Cell Types, Sources, Functions, Culture Details, and Achievable Densities in Cultivated Meat Production.

Cell Type	Cell Source	Function in Cultivated Meat	Culture Details	Achievable Cell Density* (cells/mL)	Reference
Embryonic stem cells (ESCs)	Pluripotent Stem Cells (PSCs)	Highly versatile and self-renewing cell source	DMEM + 10-20 % KOSR + bFGF	1 - 2×10^6	(Takahashi & Yamanaka, 2016)
Fibroblasts	Epithelial-mesenchymal transition and circulating bone marrow-derived fibrocytes	Produces extracellular matrix (ECM) proteins like collagen, contributing to tissue structure	DMEM + 10 % FBS + P/S	0.5 - 2×10^6	(Ben-Arye & Levenberg, 2019)
Adipocytes (Fat Cells)	Fat tissue	Contributes to flavor and juiciness	DMEM + 10 % FBS + 1 % P/S + insulin, dexamethasone	0.5 - 1.5×10^6	(Ben-Arye et al., 2020)
Bovine adipose-derived stem cells (bASCs)	Adipose tissue of cows	To differentiate into fat cells that contribute to the fat content, flavor, and texture of the lab-grown meat	DMEM with 10 % FBS, bFGF and UltraGlutamine	$10^6 – 10^7$	(Hanga et al., 2020)
BovineESC01_PluriCells	bovine (cow) embryonic stem cells	Differentiate into various cell types, like muscle and fat cells	DMEM/F12 supplemented with 0.03 % BSA.	$10^6 – 10^7$	(Kinoshita et al., 2021; Reiss et al., 2021)
PorcineESC01_PluriCells	porcine (pig) embryonic stem cells,	Differentiate into different cell types, such as muscle and fat cells, which are crucial for producing pork in a lab setting	DMEM/F12 supplemented with 0.03 % BSA.	$10^6 – 10^7$	(Kinoshita et al., 2021; Reiss et al., 2021)
OvineESC01_PluriCells	From ovine (sheep) embryonic stem cells	Differentiate into various cell types, such as muscle and fat cells, enabling the production of lab-grown lamb or mutton	DMEM/F12 supplemented with 0.03 % BSA.	$10^6 – 10^7$	(Kinoshita et al., 2021; Reiss et al., 2021)
CFS414	Embryonic fibroblasts	A foundational cell line that proliferates and differentiates into muscle tissue, essential for forming the meat product	DMEM + 10 % FBS + P/S NEAA, and 1×Sodium pyruvate	$10^5 – 10^6$	(Biegler et al., 2022)
Chinese Hamster Ovary (CHO) Cells	Epithelial cells of the ovary of the Chinese hamster	Produce essential growth factors, proteins, and help develop scalable, serum-free media for efficient and ethical meat production	HyClone ActiPro medium (Cytiva) and M1 – M4 media	$10^7 – 10^8$	(Schwarz et al., 2023)
Quail Myoblast Cell Line (QM7)	Skeletal muscle	Proliferating and differentiating into muscle fibers, forming the essential tissue structure of the meat	DMEM/F12, 2 % FBS, and 1 % P/S along with hFGF2 and HGF	$10^6 – 10^7$	(Perreault et al., 2023)
LRM Cells	Cell line derived from the caudal skeletal muscle of L. Rohita (a freshwater carp)	To create muscle tissue that mimics the texture and flavor of real fish, enhancing sustainability and authenticity.	L-15 with 10 % FBS and 10 ng/ml bFGF	$10^6 – 10^7$	(Goswami, Pinto, Yashwanth, Sathiyanarayanan, & Ovissipour, 2023)
Immortalized porcine muscle satellite cell	Immortalized porcine preadipocytes	Produce the fat content necessary for pork products, contributing to flavor and texture.	DMEM + 10 % FBS + P/S and bFGF	$10^6 – 10^7$	(Cheng et al., 2023)
Primary chicken embryonic fibroblast	From Chicken breeds	Support cell proliferation, produce extracellular matrix components, and aid in muscle development by mimicking the natural environment of muscle tissue.	DMEM10 culture medium supplemented with 0.1 % (v/v) Pluronic F-68	1.08×10^7	(Pasitka et al., 2023)
Bovine satellite cells (bSCs)	Isolated from bovine skeletal muscle tissue.	Enables incorporation of the scaffold into the final cultivated-meat product (on mycelium carriers)	F-10 + 20 % FBS + FGF2 (5 ng/mL) + antibiotics.	0.5 - 5×10^6	(Ogawa, Kermani, Huynh, Baar, Leach, & Block, 2024)
Bovine Adipose-Derived Stem Cells (BASCs)	Bovine carcasses (slaughterhouse by-products).	Demonstrates that bovine fat cells can survive, proliferate, and differentiate in fully defined serum-free medium, reducing costs and ethical concerns associated with FBS.	DMEM/F12 (high glucose), Insulin (10 μg/mL), Transferrin (5 μg/mL), Selenium (5 ng/mL), Ascorbic acid (50 μM), bFGF (5 ng/mL), EGF (10 ng/mL)	1×10^6	(Levenberg et al., 2005; Xuan et al., 2025)
Muscle satellite cells (PMMSC)	red seabream (Pagrus major)	These satellite cell lines are intended for cultivated seafood production; i.e. as the muscle / flesh-generating cells in cell-based fish meat.	L-15 medium + 10 - 20 % FBS	2.1×10^6	(Ulagesan, Krishnan, Nam, & Choi, 2025)
Chicken satellite cells (CSCs)	Pectoralis major muscle of broiler chickens (Gallus gallus domesticus)	The chicken satellite cells were used for myogenic proliferation and differentiation, forming multinucleated myotubes that mimic skeletal muscle fibers.	High-glucose DMEM + 10 % FBS + 1 % P/S + 10 ng/mL bFGF	1.8×10^6	(Sun et al., 2025)
Muscle satellite cells (SCs)	Large yellow croaker (a marine fish)	The SCs are responsible for muscle tissue formation (myogenic differentiation) in the final cultured fish fillet product.	L-15 medium + 15 % FBS + 1 % P/S + 10 ng/mL bFGF	6.25×10^5	(X. Zhou et al., 2025)

(continued on next page)

Table 2 (*continued*)

Cell Type	Cell Source	Function in Cultivated Meat	Culture Details	Achievable Cell Density* (cells/mL)	Reference
Non-adherent insect cell line (MsNAC)	Manduca sexta (tobacco hornworm) embryonic tissues	Designed as a robust, scalable cell source for biomass generation in cultivated meat systems; potentially useful for insect-based or hybrid meat analogs.	Cultured for 7 days in Ex-Cell 420 Insect Cell Medium	2×10^7	(Letcher, Calkins, Clausi, McCreary, Trimmer, & Kaplan, 2025)
Immortalized murine myoblast cells (C2C12) cells	Skeletal muscle of C3H mice	C2C12 cells contribute the muscle / animal protein component in the final hybrid food product.	High-glucose DMEM + 10 % FBS + 1 % P/S	5×10^6	(Maharjan et al., 2025)

DMEM, Dulbecco's Modified Eagle Medium; FBS, Fetal Bovine Serum; P/S, penicillin/streptomycin; bFGF, basic fibroblast growth factor; HS, Horse Serum; hPL, Human Platelet Lysate; EGM-2, Endothelial Growth Medium-2; KOSR, Knockout Serum Replacement; hFGF2 and HGF, Human Fibroblast Growth Factor 2 and Hepatocyte Growth Factor; EGM, Endothelial Cell Growth Medium; BSA, Bovine Serum Albumin; NEAA, Non-Essential Amino Acids.

* Achievable Cell Density refers to the typical concentration of cells that can be sustained in a bioreactor environment during the production of cultivated meat.

strength, charge, and diameter to aid protein synthesis and cell differentiation, and providing cyclic stretching to assist muscle cell maturation (Mihic et al., 2014).

In addition to innovations in materials, ultrafine bubbles (UFBs) are gaining attention in various industries as a new type of gas nanocarrier (Tran et al., 2023). They are produced using high-frequency or high-pressure methods, creating extremely small gas-filled bubbles, typically less than 200 nanometers in diameter (Miyamoto et al., 2023), which exhibit unique properties due to their small size and stability (Noguchi et al., 2017). Due to their small size, they have a large reactive surface area and are usually negatively charged, which prolongs their lifespan in liquids (Noguchi et al., 2017). This negative charge can attract ions from the culture medium, facilitating nutrient delivery. UFBs are currently showing excellent applications in fields including cosmetics, pharmaceuticals, and agriculture (Park et al., 2022). Since UFBs are gas-based, they can switch between gases, such as oxygen, hydrogen, and carbon dioxide. They are often used to carry H_2 or O_3 filled UFBs water, which has strong bactericidal activity (Morishita et al., 2022). More importantly, as a nanocarrier, UFBs can quickly deliver nutrients and adjust the gas environment to stimulate cell growth, shorten doubling time, and increase total cell biomass (Tran et al., 2023). Other methods used to obtain high cell density for different cell types are summarized in Table 2. As the industry strives for commercial traction, setting a baseline density of minimally 100g/L of cell mass becomes imperative to unlock cost-of-goods benefits and establish the economic viability of CM production. Development of other complementary technologies for use in bioreactors such as micro/nano-aeration will also be necessary.

3.3. *Reducing cultivated meat costs through biochemical innovations*

According to the Good Food Institute (GFI) report "Trends in Cultivated Meat Scale-Up and Bioprocessing," the total global production of CM is projected to reach 125,000 tonnes by 2026 (Tavan et al., 2025). In comparison, McKinsey & Company in its report "Cultivated Meat: Out of the Lab, Into the Frying Pan" estimated that achieving a USD 25 billion market by 2030 would require an annual production capacity of approximately 1.5 million tonnes. However, this remains negligible compared to the OECD-FAO Agricultural Outlook 2025 – 2034, which estimated global conventional meat production at 365 million tonnes in 2024. In addition, according to U.S. Department of Agriculture reports (Skorbiansky et al., 2024), the average wholesale choice beef price to retail in 2024 was around USD $7.3/kg. To make CM competitive in the market, its production cost must be reduced to below USD $5/kg (Specht et al., 2018). Therefore, beyond scaling up production, cost reduction remains an urgent priority for the CM industry. It is estimated that 10^{14} cells are needed to produce 1 ton of CM, requiring thousands of liters of culture medium, with up to 55-95 % of the budget allocated to culture medium (Chen et al., 2022). Negulescu et al. (Negulescu et al., 2023) performed techno-economic analyses by computer-based simulations of manufacturing facilities (real or conceptual designs) based on mathematical models for mass and energy balances for each unit operation and utilizing necessary biological, engineering, and cost assumptions. For a ~262,000 L airlift reactor, the media cost needs to drop to about $0.75/L to reduce the overall cost to below $9/kg (Negulescu et al., 2023). The exorbitant costs associated with cell maintenance largely stem from the utilization of media for continuous cell culturing in CM. Cell culture use involves consuming thousands of liters of media with serum supplements, growth factors (e.g., FGF-2, VEGF, IGF-1, HGF, and PDGF-BB), and additives. The cost of media also significantly rises due to the use of pharmaceutical-grade components (Nikkhah et al., 2023; O'Neill et al., 2021). As the pursuit of a consistently abundant cell supply requires colossal volumes of media, the resulting costs will hence pose a challenge in terms of affordability and exploration by consumers (Humbird, 2021). To achieve price parity with traditional meat and significantly reduce overall production costs, the target cost of maintaining the cells should be within the range of cents per kilogram of raw materials, achievable only with cost-effective raw ingredients from waste or side streams of plant materials, such as those from soy, wheat, or barley. Currently, experiments are using biological waste materials such as soybean residue (Agnihotri et al., 2021) or orange peels (Mantzouridou et al., 2015). Following separation and purification, these materials can serve as microbial culture media, enabling the remaining nutrients (e.g., proteins and carbohydrates) to be fermented or converted into lipids (Caporusso et al., 2021). These useful nutrients are then extracted for use as alternatives to cell culture media. However, becoming a reliable source of nutrients remains highly challenging. Thus, it is necessary to find lower-cost nutrient sources, such as vitamins and minerals (Hubalek et al., 2022). Although a few studies have focused on the use of serum-free media for culturing bovine satellite cells, there is limited publicly available information on the development of affordable media and growth supplements for various species of CM (Pasitka et al., 2023). Recently, the integration of artificial intelligence (AI) and metabolic studies to expedite the development of sustainable media formulations for CM has been proposed (Nikkhah et al., 2023). Exploring alternative components and eliminating dependencies on costly external factors would simultaneously bridge the gap between economic sustainability and ethical considerations (Ramani et al., 2021).

3.4. *Cost reduction strategies in cell culture production using AI and modeling*

Recent advances in AI technologies have been increasingly applied across various domains of bioprocess optimization, including large-scale cell culture for gene therapy, biopharmaceutical production, and emerging fields such as CM. However, AI-specific studies directly targeting cost reduction strategies in CM production remain relatively limited. This section summarizes and discusses several representative studies that have explored AI-assisted process modeling and cost-efficient media optimization relevant to cellular agriculture as shown in Table 3.

To reduce serum dependence and improve scalability, Cosenza et al. (2023) developed a multi-objective Bayesian optimization pipeline that identified high-performing, low-cost serum-free media for C2C12 myoblasts, achieving 23 % higher growth with 62.5 % of the cost of the control medium (Cosenza et al., 2023). The strategy combined high-throughput screening with multi-fidelity data integration, reducing both material and laboratory costs.

In another study focused on zebrafish embryonic cells (ZEM2S), Nikkhah et al. utilized a hybrid AI approach combining Response Surface Methodology (RSM), Radial Basis Function neural networks (RBF), and a Genetic Algorithm (GA) to optimize reduced-serum culture media. This led to a 20 – 24 % cost reduction through precise adjustment of growth factor concentrations such as IGF and FGF (Nikkhah et al., 2023).

Beyond media composition, Ebrahimian et al. proposed a process-level optimization using in situ cell detachment in microcarrier cultures. By incorporating hybrid modeling and augmented Design of Experiments (DoE), the team successfully reduced handling steps and eliminated the need for costly cell-microcarrier separation, contributing to operational cost savings in adherent cell propagation (Ebrahimian et al., 2024).

For T cell therapy applications which share medium development challenges with CM. Grzesik et al. introduced a machine learning pipeline combining elastic net, random forest, and clustering algorithms to perform one-time media optimization, reducing donor-specific formulation costs while maintaining performance across variable inputs (Grzesik & Warth, 2021).

Finally, Schinn et al. demonstrated the value of genome-scale metabolic modeling combined with machine learning to predict amino acid consumption in CHO cells, enabling preemptive nutrient supplementation and reducing wasted feeds or failed runs strategies that could be adapted to animal cell-based meat systems (Schinn et al., 2021).

Together, these studies illustrate the diverse and powerful applications of AI in reducing costs in cell culture-based systems. Whether through optimizing nutrient formulations, reducing experimental trials, or improving scalability, AI has shown potential to address one of the major hurdles in CM production economic feasibility. Beyond laboratory optimization, recent perspectives also suggest that integrating AI with blockchain frameworks could further enhance data transparency, process security, and sustainability throughout the CM supply chain, reinforcing trust and efficiency in the emerging cellular agriculture ecosystem(Kaliji, Pakseresht, & Hocquette, 2025).

3.5. *Microbial risks control and challenges in scaling up the cellular agriculture industry*

According to the joint FAO and WHO report (Organization, 2023) microbial contamination remains a critical safety consideration during

Table 3
Detailed AI-Driven Cost Reduction Strategies in Cell Culture.

AI/ML Method	Application Area	Cost Reduction Strategy	Cell Type Used	Reference
RSM, RBF Neural Network, NSGA-II	Cultivated meat production, specifically targeting the development of reduced-serum culture media for zebrafish (ZEM2S) cells used in aquatic cellular agriculture systems.	Multi-objective AI-based optimization integrating RSM, RBF, and NSGA-II. Significant serum (FBS) reduction in the media formulation by replacing it with combinations of lower-cost components such as PDGF, selenium, and ascorbic acid. Use of microbial-derived growth factors instead of animal-derived ones.	ZEM2S (Zebrafish Embryonic Stem Cells)	(Nikkhah et al., 2023)
DoE/hybrid modelling approach	The optimization of the seed train and microcarrier culture process enhances the scalability and efficiency of vaccine-related biomanufacturing	Optimizing key process variables (e.g., agitation speed, cell seeding density) minimizes batch failures and improves yield, which reduces operational costs in large-scale cell culture..	MA 104 cells	(Ebrahimian et al., 2024)
Hybrid modeling/ ANN	Bioprocess development for CHO cell culture in upstream biomanufacturing.	By using hybrid models, the article aims to reduce experimental workload, improve process understanding, and enhance predictive accuracy, thereby cutting time and cost in development cycles.	CHO-K1 cells	(Bayer, Duerkop, Pörtner, & Möller, 2023)
Elastic net, random forest, and k-means clustering	The application focuses on cell and gene therapy, specifically optimizing T cell culture media for robust expansion across diverse human donors.	The study implements a one-time optimization strategy that bypasses sequential experiments by combining high-throughput screening with predictive ML modeling, reducing time, cost, and donor material usage.	primary human CD3+ T cells	(Grzesik et al., 2021)
ANN	This work is directly applied to the 3D bioprinting of cultivated meat, focusing on the creation of structured meat tissues with edible bioinks.	By predicting optimal print settings and avoiding failed prints, the approach significantly cuts down on resource waste and bioprinter operation time .	C2C12 myoblasts	(Ng & Tan, 2024)
Hybrid modelling /genome-scale metabolic network model with statistical machine learning	Applied in biopharmaceutical manufacturing, specifically for nutrient monitoring and predictive control in CHO cell-based fed-batch processes.	By forecasting amino acid depletion from routine measurements, the method enables anticipatory nutrient feeding and helps avoid failed bioreactor runs, reducing waste and increasing process reliability.	CHO cell line	(Schinn et al., 2021)
MOBO	Designing serum-free culture media for C2C12 myoblasts used in cultivated meat production.	The method reduces cost by minimizing expensive components such as serum-free, ECM-free and integrating multi-fidelity data to discover low-cost, high-growth media.	C2C12 myoblasts	(Cosenza et al., 2023)
Reinforcement learning	ML was applied to cell quality prediction, culture media optimization, 3D bioprinting, contamination detection, and sensory analysis across all production stages.	Strategies include serum-free or reduced-serum media design, hybrid meat using low-percentage cultivated cells, and predictive models to reduce experimental costs.	pMuSCs	(Ng et al., 2025)

AI, Artificial Intelligence; ML, Machine Learning; RSM, Response Surface Methodology; RBF, Radial Basis Function Neural Network, NSGA-II, Non-dominated Sorting Genetic Algorithm II;PDGF, Platelet-Derived Growth Factor ; DoE, Design of Experiments; ANN, Artificial Neural Networks; CHO, Chinese Hamster Ovary; MOBO, Multi-objective Bayesian Optimization; ECM, Extra-Cellularmatrix, pMuScs, Porcine Muscle Stem Cells the scale-up of cellular agriculture systems. While CM offers significant advantages in reducing zoonotic transmission and minimizing contamination risks compared to conventional meat processing, the FAO report highlights that potential microbial hazards can still emerge throughout cell sourcing, culture, and harvesting stages. As production transitions from laboratory to industrial scale, maintaining aseptic integrity, controlling biofilm formation, and preventing cross-contamination within bioreactors become increasingly complex. These challenges underscore the necessity of developing specialized microbial control strategies tailored to large-scale CM manufacturing environments. Traditional meat production accounts for approximately 70 % of global antibiotic use (Van Boeckel et al., 2019), and the misuse of antibiotics contributes to the global issue of antibiotic-resistant bacterial strains (Silbergeld et al., 2008). CM produced in a controlled and sterile environment, presents a viable solution for drastically reducing antibiotic usage (Hadi & Brightwell, 2021). However, cell cultures remain susceptible to contamination even in such controlled settings (Mahmood & Ali, 2017). While many CM companies claim that they can culture cells for human consumption without antibiotics, scaling up production while maintaining sterile conditions remains a significant challenge for the industry (O'Neill et al., 2021; Ong et al., 2021). Recent studies indicate that CM companies experience an average of 11.2 % microbiological contamination in industrial-scale production, with bacterial contamination being the main cause. In more complex production processes, including cell culture and manufacturing, the risk of contamination is even higher, reaching up to 19.5 % (Powell et al., 2025). To address this, infection sensing and mitigation strategies are key areas for process optimization illustrated in Fig. 1, alongside providing a clean environment. Conventional sensing technologies include microfluidics (Marques & Szita, 2017), biochips (Y. Zhang et al., 2022), DNA extraction and amplification (Leonardo et al., 2021), protein detection, pathogen detection (J. Zhou et al., 2020), optical detection, and electrochemical biosensors (Stern Bauer, Yakobi, Hurevich, Yitzchaik, & Hayouka, 2023). These methods are already widely used in biological and biomedical fields. However, in scaling up CM production, where total culture volumes can reach thousands of liters, and the process duration may extend over several weeks to achieve sufficient cell density and yield, any early-stage pathogen or bacterial contamination levels are often very low. Traditional quantitative Polymerase Chain Reaction (qPCR) detection methods are time-consuming and costly, as they require isolating DNA from complex bioreactor environments. Electrochemical biosensors, therefore, offer a potential alternative, enabling rapid and highly sensitive detection compared to traditional protein detection methods (Xu et al., 2020). These biosensors can detect bacteria at very low concentrations, with a sensitivity reaching the pg/mL level, facilitating early-stage contamination detection (L. Zhang et al., 2023). Current detection approaches are categorized into invasive, non-invasive, and indirect methods (Biechele et al., 2015). Invasive methods involve directly inserting sensing probes into the culture medium, while non-invasive methods use optical or ultrasonic techniques for detection. Indirect methods involve extracting samples of the medium for laboratory testing (Biechele et al., 2015; Djisalov et al., 2021). For accurate results, invasive and indirect methods are considered more feasible within the CM production process, although they increase the risk of contamination. As a result, mitigation strategies become crucial, focusing on reducing bacterial growth through the addition of substances like lipids (Aldayel et al., 2023), fatty acid (Casillas-Vargas et al., 2021), peptides (Stern Bauer et al., 2023; Yakir et al., 2025) , or glycans (Behren & Westerlind, 2023), which can inhibit bacterial proliferation or exhibit strong antibacterial effects. These strategies provide preventive measures that help maintain bioreactor conditions, reducing the need for frequent sensing and minimizing contamination risks. However, the development of novel, safe, and resistance-proof antimicrobial agents is essential to overcome these challenges and ensure the continued safety and sustainability of CM production (Srutee et al., 2022).

3.6. Technologies to characterize and explore the taste and textures of cultivated meat

Early reviews, such as (Fraeye et al., 2020), highlighted that many sensory and nutritional properties of CM remain uncertain due to limited empirical data. Building upon these identified gaps, recent research has increasingly focused on technological strategies to reproduce the taste, texture, and appearance of conventional meat. While nutritional aspects remain important, the primary challenges for consumer acceptance now lie in replicating flavor and texture. A major hurdle of CM production is therefore the creation of products with taste and structural profiles that closely resemble slaughtered meat. Successful market integration of CM will depend on extensive efforts to mirror the intricate 3D macrostructures of muscle and fat tissues, as well as their characteristic flavor profiles, as illustrated in Fig. 2 (Starowicz et al., 2022).

The taste characteristics of CM is also a critical factor that needs more invested efforts beyond just pre-cooking marinations (To et al., 2024). The unique umami taste of individual traditional meat is dependent on the amino acid and nucleotide profiles, the presence of

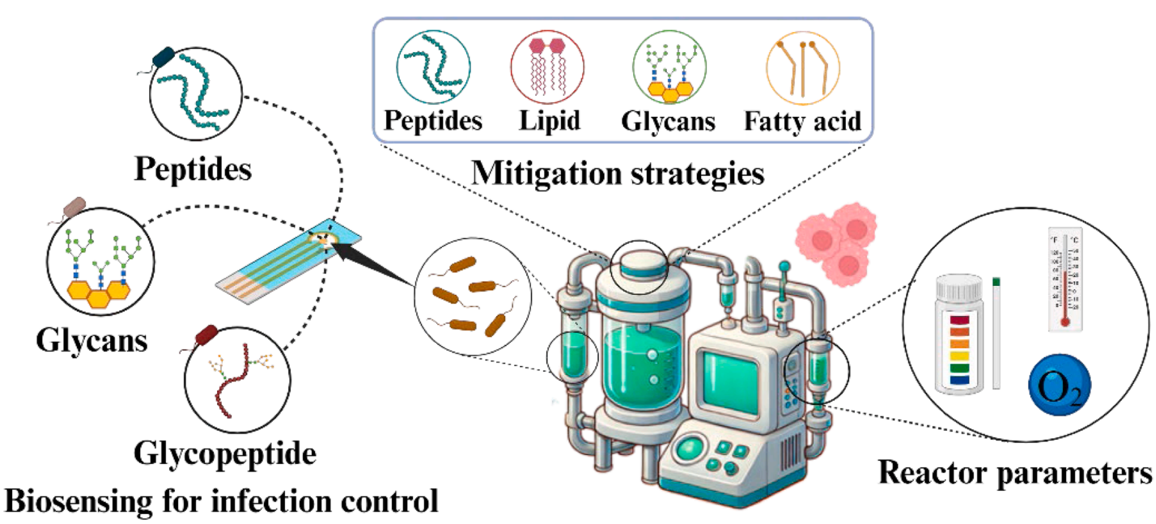


Fig. 1. Microbial risk control is crucial in the cultivated meat(CM) process. Electrochemical sensors are used to detect potential contamination risks, while novel mitigation agents such as peptides, glycans, and lipids are employed to control bacterial growth, ensuring a safe and clean production environment throughout the CM process.

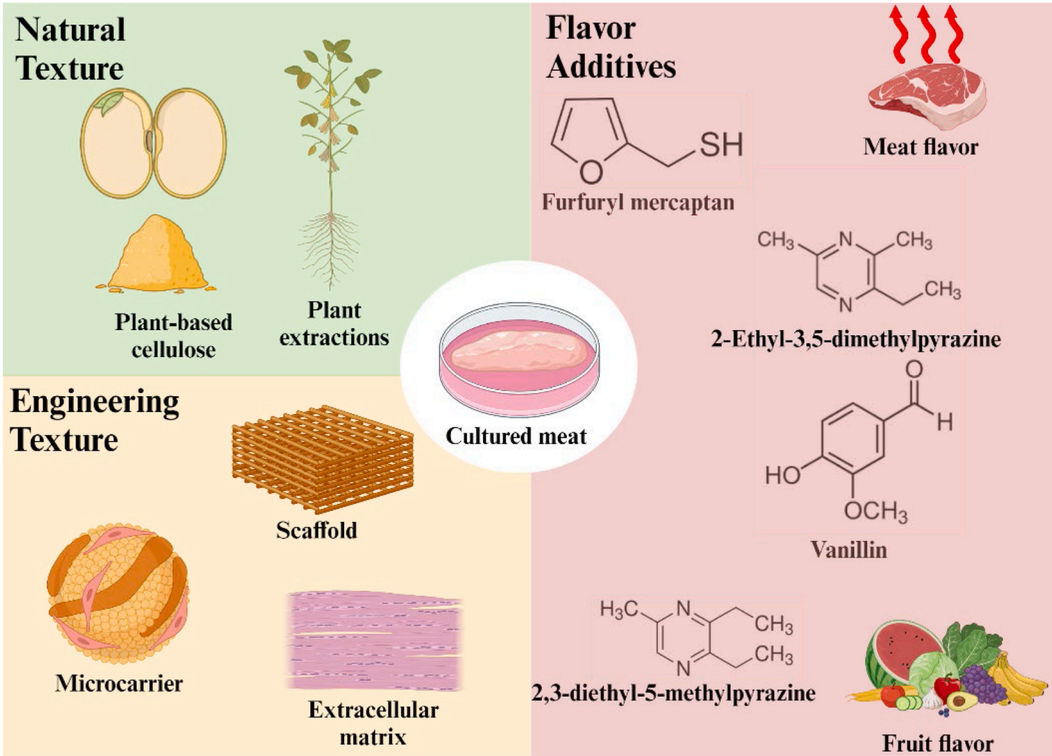


Fig. 2. Current technologies aim to enhance the texture and flavor of cultivated meat (CM) through methods such as using natural extracts like plant-based cellulose, and engineering texture using edible microcarriers, bio-scaffolds, and cell-derived extracellular matrix (ECM). Additionally, flavor enhancers like furfuryl mercaptan can be added to provide a meat-like taste, while 2,3-diethyl-5-methylpyrazine imparts a nutty umami flavor.

heme, as well as its blood and fat content (Joo et al., 2022; Kim et al., 2023). In a high-temperature process (cooking), the amino group accelerates its reaction with sugars, leading to the Maillard reaction, which imparts a unique flavor to the meat. Impossible Foods is renowned for its cultured heme to replicate the meat flavors in its alternative protein products, and other startups such as tHEMEat company have also developed alternative sustainable methods of obtaining heme that can be incorporated into CM products. ImpacFat company is currently championing efforts of growing fish-derived adipocytes that is touted to significantly contribute to the fat-derived flavor of meat, as well as replicating its nutritional content (Sugii et al., 2022; Yuen Jr et al., 2023). Recently, Hong *et al.* researched a flavor-switchable scaffold. Traditional synthetic volatile flavor compounds (SFC) (Lee et al., 2024), can impart flavor but are released quickly over time into the air; for example, sulfur-containing compounds such as furfuryl mercaptan, found in roasted meat (Huang et al., 2023). Cultivating meat is very time-consuming, and typical SFCs cannot be retained in the meat. Therefore, furfuryl mercaptan was used to modify thiol-end groups on a 3D scaffold backbone, allowing the volatile furfuryl mercaptan to remain stable on CM. Later, during the cooking process, the SFC is released, imparting flavor to the CM. This study also offers a method for providing long-lasting flavor (Lee et al., 2024).

Taste is also influenced by mouthfeel, which is heavily dependent on the structure of the CM product (Bomkamp et al., 2022). The integration of scaffolds plays a crucial role in the commercial success of CM by not only replicating the taste of conventional meat but also by promoting visual similarity and facilitating the transition from traditional meat products (Broucke et al., 2023). 3D scaffolds have been traditionally utilized for engineering cell-based constructs that mimic the physical characteristics of biological tissues while promoting the attachment and culture of specific cells within and would thus be naturally applied to shaping CM products (Rao et al., 2023). At the same time, using some natural sources as edible scaffolds is also a current research direction (Mariano Jr et al., 2024). Most of the approaches using methods such as 3D printing, electrospinning, edible film, cellulose, and decellularization scaffolds have very low throughput or high cost of incorporation and thus are unlikely to be attractive for mass manufacturing (Kolodkin-Gal et al., 2023; Reiss et al., 2021). While these advancements showcase great promise, challenges persist in the size limitations of the structures that can be created due to mass transfer constraints for nutrients and oxygen and the potential of scaling up the techniques to commercial scales (Rao et al., 2023). Audra labs is among the few emerging companies that have utilized a simple and scalable technology to develop realistic fibrous scaffolds to mimic the directional growth of muscle tissues and produce realistic meat-like textures from visual and taste aspects (A. E. A. d. Santos et al., 2024). In recent years, the adaptation of microcarrier technology from the biomedical industry has also emerged as a transformative solution in cultivating anchorage-dependent cells in free suspension to facilitate expansion to high densities via suspension cultures, promoting ease of cell recovery, and simultaneously allow a degree of structuring to form textured products (Koh et al., 2020; Ornelas-González et al., 2021). Companies like SmartMCs are among several industrial players providing edible and dissolvable microcarriers tailored for the CM industry. Exploration of these technological advancements would thus highlight the strides made in the industry while also surfacing the complexities that researchers and companies grapple with as they endeavor to capture characteristics of traditional meat products to drive the success of CM.

4. Sustainable resources for sustainable production

In alignment with the narrative of being a sustainable alternative to meat production, it is important to have an in-depth cradle-to-grave analysis and scrutinize the intricate interplay of various factors throughout the CM production process to ensure it meets or surpasses the broader goal of mitigating environmental impact and resource depletion (Min & Cho, 2024). The successful implementation of sustainable processes hinges on understanding, evaluating, and quantifying the net impact on the climate, considering both direct and indirect emissions throughout the production chain. By adopting a comprehensive approach to sustainability, the CM industry would contribute to the global shift towards eco-friendly practices and establish itself as a viable and environmentally conscious alternative to conventional meat production. The section underscores the significance of considering energy use as a critical determinant in assessing the overall eco-friendliness of CM, prompting the exploration of innovative waste processing and utilization methods to optimize efficiency while minimizing environmental repercussions, and is broken down into two subsections of major factors that will be instrumental in ensuring that the CM economy aligns with broader ecological preservation objectives.

4.1. Efficient waste stream valorization

The utilization of agri-food waste streams in CM presents an opportunity to explore potential advantages of CM products relative to traditional meat production, which has been reported to be associated with environmental pressures such as GHG emissions, deforestation, and water use depending on production systems and regional contexts (Negulescu et al., 2023; Sinke et al., 2023). Early life-cycle assessments (LCAs) by (Tuomisto & Teixeira de Mattos, 2011) suggested that CM could potentially reduce GHG emissions by 78 – 96 %, land use by 99 %, and water use by 82 – 96 % compared with conventional beef under specific, hypothetical production assumptions. However, subsequent critical reviews have emphasized that these early LCA results are highly sensitive to assumptions regarding system boundaries, energy demand, and energy mix, and should therefore be interpreted as prospective, scenario-dependent estimates rather than confirmed environmental advantages (Rodríguez Escobar et al., 2021). Subsequent techno-economic and systems-level simulations have further explored this potential under defined conditions (Roxburgh et al., 2025) used an agent-based model (ABM) integrating national agricultural and energy data to simulate carbon-tax scenarios, revealing that under specific policy and low-carbon energy assumptions, a large-scale transition to cultivated proteins could lower agricultural emissions by up to 97 % while simultaneously mitigating national contributions to global warming. Similarly, (Kossmann et al., 2025) employed a linear-programming (LP) optimization model to evaluate agricultural feedstock production for CM in southern Germany. Their simulations incorporated crop-rotation constraints, nutrient-extraction efficiencies, and optional solar-energy integration. Results showed that, in the most land-efficient scenario combining high nutrient-recovery rates with renewable-energy inputs CM required approximately 0.8 ha per ton of protein, slightly lower than conventional pork (1.0 – 1.2 ha per ton), whereas less optimized settings increased land demand up to 2 ha per ton. In line with recent analyses, these land-use estimates should be interpreted with respect to arable land demand and opportunity cost rather than total land occupation, given that a substantial share of land used in ruminant systems consists of grasslands unsuitable for crop production.(Peyraud et al., 2025) This analysis highlighted that CM's land-use advantage is not inherent but contingent upon efficient nutrient sourcing and sustainable energy systems. In parallel, (Ng & Tan, 2025) highlighted the role of machine-learning-driven simulation and predictive control to improve CM process sustainability optimizing nutrient composition, scaffold architecture, and contamination detection to minimize material losses and energy consumption throughout the production pipeline. Taken together, these modeling and simulation studies indicate that CM's potential to reduce GHG emissions and land pressure is conditional and strongly dependent on technological efficiency, energy sourcing, and system design, rather than an intrinsic property of the production concept itself. Accordingly, simulation-guided optimization whether through LCA, ABM, LP, or ML frameworks should be viewed as an essential tool for exploring feasible decarbonization pathways rather than providing definitive environmental outcomes.

Nevertheless, one major sustainability bottleneck in large-scale CM production remains the intensive use of clean water and the generation of nutrient-rich liquid effluents during continuous perfusion culture (Shimizu et al., 2021). As production volumes scale up, these spent-media streams could contribute to eutrophication and nitrogen pollution if discharged untreated. Recent studies emphasize that developing closed-loop media recycling systems is essential to reduce both the environmental footprint and production cost of CM. According to (Wang et al., 2025), integrating media reuse and nutrient recovery into the process design can substantially reduce life-cycle GHG emissions, water depletion, and eutrophication potential, as simulated through LCA-based sustainability modeling. In parallel, (Pakbin et al., 2025) experimentally optimized an ammonia removal strategy for spent-media recycling using a response-surface methodology, achieving over 82 % ammonia removal at pH 12 within 15 min while preserving glucose integrity. When the treated media was reformulated with 50 % fresh medium, lamb satellite cells exhibited normal proliferation and morphology, confirming its biological feasibility. Collectively, these findings demonstrate that targeted removal of toxic metabolites particularly ammonium coupled with nutrient recovery and reinfusion of key components such as glucose, amino acids, and growth factors, can effectively close the resource loop and enable repeated media use.

To achieve media recycling and reuse, existing technologies can monitor the consumption of nutrients in the media, such as glucose and lactate measurement, while also tracking pH levels. Additionally, HPLC can be used to monitor amino acid consumption, O_2/CO_2 concentration can be tracked, and NMR can be employed for metabolite identification. However, these comprehensive assessments require complex techniques, making the reinfusion of nutrients back into the feed media a significant technical challenge. Current approaches include developing low-cost adsorbent materials for ammonia nitrogen removal (Feng et al., 2023) or using natural substances or extracts, such as heterotrophic microalgae (Lowrey et al., 2016), to absorb nutrients and facilitate nutrient recycling. According to the results of Shimizu et al (Haraguchi & Shimizu, 2021), when mammalian myoblasts are used in CM, the cells significantly consume glucose and glutamine in the culture medium. However, the utilization of other nutrients is less efficient. To address this, they used the microalgae *Chlorococcum littorale* (*C. littorale*) and *Chlorella vulgaris* (*C. vulgaris*) for secondary cultivation and recycling of the medium. The results showed that *C. littorale* and *C. vulgaris* consumed 80 % of ammonia, 26 % of amino acids, and 16 % and 15 % of phosphorus, respectively (Haraguchi et al., 2021). Unused nutrients from the primary culture can be reutilized, potentially producing biofuels and removing excess ammonia generated during cell culture. Additionally, this process could yield high-value products such as omega-3 fatty acids and other lipids for secondary fermentation (Lowrey et al., 2016). This approach enables the secondary use of medium, creating added value and promoting biological purification. Alternatively, synthesizing adsorber material to adsorb lactate from culture media and aqueous solutions has proven effective in reducing lactate concentration, thus promoting cell growth and optimizing culture conditions (Podolinnaia et al., 2023). Many researchers are actively studying the circular cell culture (CCC) system (Haraguchi et al., 2022). The concept involves combining mammalian muscle cell culture with microbial cultivation, such as microalgal culture (Haraguchi et al., 2022). This process uses cell culture waste medium, which is supplemented with necessary nutrients for microalgal culture. Subsequently, nutrients are extracted from the microalgae and used as culture medium for mammalian muscle cell culture, thus achieving CCC. There will also be a foreseeable need to effectively valorize the waste streams of the cell culture process by extracting and recycling waste metabolites such as ammonia, lactate, CO_2 from the spent media, where ammonia could be converted to fertilizers, lactic acid to bioplastics and CO_2 could be fed to algal cultures, which in turn can be the amino acid feedstock for CM (Yang et al., 2023).

Another aspect to explore is the feasibility of using agri-food waste streams as viable resources to support the production of cultured cells, as a sustainable, edible, and renewable source (Kawecki et al., 2024). For example, research by Gaudette et al (Perreault et al., 2023), indicates that harvest waste such as corn husks or jackfruit rinds represent abundant sources of cellulose for scaffolds. After decellularization, these plant-based recycled scaffolds, when seeded with bovine satellite cells (BSCs), have shown increased protein yields (Perreault et al., 2023), suggesting a potential research direction. This not only facilitates the reuse of agri-food waste but also has the potential to achieve a genuine CCC system.

4.2. Maximizing renewable resources and sustainable energies

The CM industry faces a critical challenge in maximizing renewable resource utilization while minimizing environmental impacts across its supply chain (Mariano Jr et al., 2025). Although CM production has been proposed to potentially reduce land and water use compared with conventional meat systems, such outcomes remain conditional and highly dependent on production scale, system design, and energy sourcing. Large-scale CM manufacturing is currently energy-intensive, particularly in bioreactor operation and culture media preparation, which require substantial energy, water input, and temperature control. While the adoption of renewable resources and sustainable energy systems represents a general trend across production sectors rather than a CM-specific characteristic, it is particularly relevant in the context of CM given the high energy demands associated with large-scale bioprocessing. Accordingly, the integration of renewable energy sources and improvements in resource circularity are considered important strategies for advancing the long-term sustainability of CM production (Negulescu et al., 2023). Recent studies have explored strategies to reduce energy and resource consumption, including media recycling and renewable power integration (Wimble et al., 2025). While methods for reusing culture medium have been proposed, wastewater treatment continues to present a major bottleneck. Approaches such as physical filtration, electrochemical and biological treatment, membrane separation, evaporation, and ion exchange (Cui et al., 2023) have been investigated to remove cell debris, protein precipitates, and toxic residues. However, the technical challenge of reusing purified media directly within bioreactors remains unresolved, and research in this area is still limited. (Cui et al., 2023).

To reduce the carbon footprint, CM manufacturing facilities must transition to renewable energy sources such as wind, geothermal, and solar power, which can substantially enhance sustainability (Østergaard et al., 2020). Among these, solar and wind energy have demonstrated particularly strong environmental benefits, second only to cell-line optimization and outperform media reformulation strategies in reducing emissions (Krasnyanskyy, 2025; Peter et al., 2022). Changing the cell line can significantly shorten doubling time and reduce media consumption, while renewable power directly decreases fossil fuel dependence and thermal energy conversion, resulting in a more impactful environmental benefit. Solar-powered bioreactor systems are also being developed to advance this approach, and solar-assisted wastewater treatment shows additional promise (Hafeez et al., 2021). Nevertheless, the high capital cost and spatial requirements for energy collection remain barriers, particularly since CM aims to be a space-efficient alternative to conventional livestock systems.

Emerging technologies now explore self-sustaining energy solutions. For instance, self-powered microfluidic systems can harvest chemical energy from microbial digestion or redox reactions to drive sensors within bioreactors (Wu et al., 2020). Likewise, triboelectric nanogenerators could convert mechanical friction from continuous stirring into electrical energy to power in situ biological sensors (Qu et al., 2023). Although these approaches are still conceptual, they illustrate the direction toward energy autonomy and reduced grid dependence. Achieving such a system will require a comprehensive LCA to evaluate each energy-intensive process from waste treatment to cell harvest and ensure that CM production remains genuinely sustainable and environmentally sound.

5. Conclusion and future directions

This review highlights current research directions exploring CM as a potential pathway toward more sustainable meat alternatives, drawing on advances across science, engineering, and economics. These interdisciplinary efforts seek to address significant commercial and technical challenges that currently limit large-scale adoption, rather than presupposing their resolution. While progress in these areas may contribute to improved cost efficiency and environmental performance, the extent to which CM can become a scalable and resource-efficient alternative to conventional meat production remains dependent on future technological development and system-level validation. As highlighted by (Olenic & Thorrez, 2023), many of the anticipated benefits of CM remain based on assumptions rather than experimentally validated or industrially demonstrated evidence, underscoring the need for cautious interpretation of sustainability and scalability claims. Key challenges remain, particularly in the development of robust cell lines that can proliferate and differentiate efficiently. Solutions may involve optimizing culture media to maintain stemness or developing engineered cell lines with indefinite growth potential. Reducing costs and minimizing environmental impact in CM production will require innovative feeding strategies and lower-cost, metabolically efficient media components. This highlights the need for deeper research into the molecular mechanisms underlying cell metabolism. Ensuring the quality and safety of CM is another critical concern. While aseptic production environments help control contamination, further studies are needed to understand how cell type, differentiation, and tissue structure impact food functionality. Additionally, addressing safety concerns such as contamination, toxicity, allergenicity, and genetic stability will be essential as the industry advances. In the future, overcoming these technical and scientific hurdles will be pivotal for making CM a viable, safe, and accepted alternative to traditional meat production.

Ethical statement - studies in humans and animals

Authors declare that no animals no humans were involved in the studies described in this research work.

CRediT authorship contribution statement

Yu-Chien Lin: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Naiem Ahmad Wani:** Writing – original draft, Formal analysis, Data curation. **Idan Yakir:** Data curation. **Xue Wei Liu:** Supervision. **Assaf Friedler:** Supervision, Funding acquisition. **Mattan Hurevich:** Supervision. **Weibiao Zhou:** Supervision. **Zvi Hayouka:** Writing – review & editing, Supervision, Formal analysis. **Steve Oh:** Writing – review & editing, Writing – original draft, Supervision, Formal analysis, Data curation. **Shlomo Yitzchaik:** Supervision, Resources, Funding acquisition. **Nam-Joon Cho:** Writing – review & editing, Supervision, Resources, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This research is supported by the National Research Foundation, Prime Minister's Office, Singapore, under its Campus for Research Excellence and Technological Enterprise (CREATE) programme, through the Cellular Agriculture Programme (CellAg) No:370184512.

Data availability

No data was used for the research described in the article.

References

Agnihotri, R., Pandey, A., Bharti, A., Chourasiya, D., Maheshwari, H.S., Ramesh, A., Sharma, M.P., 2021. Soybean processing mill waste plus vermicompost enhances arbuscular mycorrhizal fungus inoculum production. Curr. Microbiol. 78 (7), 2595–2607.

M.H.Z.S. Aldayel, T.S., Badran, M., Alomrani, A., AlFaris, N.A., Altamimi, J., Alqahtani, A., Orfali, R., 2023. Chitosan-coated solid lipid nanoparticles as an efficient avenue for boosted biological activities of aloe perryi: antioxidant, antibacterial, and anticancer potential Molecules 28 (8), 3569.

Allan, S.J., De Bank, P.A., Ellis, M.J., 2019. Bioprocess design considerations for cultured meat production with a focus on the expansion bioreactor. Front. Sustain. Food Syst. 3, 44.

Bayer, B., Duerkop, M., Pörtner, R., Möller, J., 2023. Comparison of mechanistic and hybrid modeling approaches for characterization of a CHO cultivation process: requirements, pitfalls and solution paths. Biotechnol. J. 18 (1), 2200381.

Behren, S., Westerlind, U., 2023. Novel approaches to design glycan-based antibacterial inhibitors. Eur. J. Org. Chem. 26 (1), e202200795.

Ben-Arye, T., Levenberg, S., 2019. Tissue engineering for clean meat production. Front. Sustain. Food Syst. 3, 46.

Ben-Arye, T., Shandalov, Y., Ben-Shaul, S., Landau, S., Zagury, Y., Ianovici, I., Levenberg, S., 2020. Textured soy protein scaffolds enable the generation of three-dimensional bovine skeletal muscle tissue for cell-based meat. Nat. Food 1 (4), 210–220.

Bennie, R.Z., Ogilvie, O.J., Loo, L.S.W., Zhou, H., Ng, S.K., Jin, A., Domigan, L.J., 2025. A risk-based approach can guide safe cell line development and cell banking for scaled-up cultivated meat production. Nat. Food 6 (1), 25–30.

Biechele, P., Busse, C., Solle, D., Scheper, T., Reardon, K., 2015. Sensor systems for bioprocess monitoring. Eng. Life Sci. 15 (5), 469–488.

Biegler, M.T., Fedrigo, O., Collier, P., Mountcastle, J., Haase, B., Tilgner, H.U., Jarvis, E. D., 2022. Induction of an immortalized songbird cell line allows for gene characterization and knockout by CRISPR-Cas9. Sci. Rep. 12 (1), 4369.

Bogueva, D., Marinova, D., 2020. Cultured meat and Australia's generation Z. Front. Nutr. 7, 148.

Bomkamp, C., Skaalure, S.C., Fernando, G.F., Ben-Arye, T., Swartz, E.W., Specht, E.A., 2022. Scaffolding biomaterials for 3D cultivated meat: prospects and challenges. Adv. Sci. 9 (3), 2102908.

Broucke, K., Van Pamel, E., Van Coillie, E., Herman, L., Van Royen, G., 2023. Cultured meat and challenges ahead: A review on nutritional, technofunctional and sensorial properties, safety and legislation. Meat sci. 195, 109006.

Bryant, C., van Nek, L., Rolland, N.C., 2020. European markets for cultured meat: A comparison of Germany and France. Foods 9 (9), 1152.

Bui, H.T., Filimonau, V., Ermolaev, V.A., 2025. Cultivated meat in tourism and hospitality: setting the scene and outlining future research agenda. J. Foodserv. Bus. Res. 28 (4), 843–854.

Cai, J., Wang, S., Li, Y., Dong, S., Liang, J., Liu, Y., Li, S., 2024. Industrialization progress and challenges of cultivated meat. J. Future Foods 4 (2), 119–127.

Caporusso, A., Capece, A., De Bari, I., 2021. Oleaginous yeasts as cell factories for the sustainable production of microbial lipids by the valorization of agri-food wastes. Fermentation 7 (2), 50.

Casillas-Vargas, G., Ocasio-Malavé, C., Medina, S., Morales-Guzmán, C., Del Valle, R.G., Carballeira, N.M., Sanabria-Ríos, D.J., 2021. Antibacterial fatty acids: an update of possible mechanisms of action and implications in the development of the next-generation of antibacterial agents. Prog. Lipid Res. 82, 101093.

Castellani, P., Cassia, F., Vargas-Sánchez, A., Giaretta, E., 2025. Food innovation towards a sustainable world: A study on intention to purchase lab-grown meat. Technol. Forecast. Soc. Change 211, 123912.

Chen, L., Guttieres, D., Koenigsberg, A., Barone, P.W., Sinskey, A.J., Springs, S.L., 2022. Large-scale cultured meat production: trends, challenges and promising biomanufacturing technologies. Biomaterials 280, 121274.

Cheng, Y.-M., Hong, P.-C., Song, M.-M., Zhu, H.-N., Qin, J., Zhang, Z.-D., Zhu, W.-Y., 2023. An immortal porcine preadipocyte cell strain for efficient production of cell-cultured fat. Commun. Biol. 6 (1), 1202.

Chriki, S., Ellies-Oury, M.-P., Hocquette, J.-F., 2022. Is "cultured meat" a viable alternative to slaughtering animals and a good comprise between animal welfare and human expectations? Anim. Front. 12 (1), 35–42.

Chriki, S., Hallman, W., Hocquette, J.-F., Ellies-Oury, M.-P., Takeuchi, M., 2025. Food culture and cell-culture: technical, ethical and social frontiers. npj Sci. Food 9 (1), 49.

Cosenza, Z., Block, D.E., Baar, K., Chen, X., 2023. Multi-objective Bayesian algorithm automatically discovers low-cost high-growth serum-free media for cellular agriculture application. Eng. Life Sci. 23 (8), e2300005.

Coucke, N., Slabbinck, H., Vermeir, I., 2023. Consumer preferences towards plant-based, hybrid and cultivated meat analogues offered in different meal contexts and at various consumption moments: A choice-based conjoint experimental design and an online survey. Food Qual. Prefer. 112, 105006.

Cui, L., Wang, P., Che, H., Chen, J., Liu, B., Ao, Y., 2023. Solar-driven interfacial water evaporation for wastewater purification: recent advances and challenges. Chem. Eng. J., 147158

Djisalov, M., Knežić, T., Podunavac, I., Živojević, K., Radonic, V., Knežević, N.Ž., Gadjanski, I., 2021. Cultivating multidisciplinarity: manufacturing and sensing challenges in cultured meat production. Biology 10 (3), 204.

Dvash, T., Lavon, N., 2024. Cultivated meat: disruptive technology for sustainable meat production. Cellular Agriculture. Elsevier, pp. 11–28.

Ebrahimian, A., Schalk, M., Dürkop, M., Maurer, M., Bliem, R., Kühnel, H., 2024. Seed train optimization in microcarrier-based cell culture post In situ cell detachment through scale-down hybrid modeling. Bioengineering 11 (3), 268.

Feng, L., Qiu, T., Yan, H., Liu, C., Chen, Y., Zhou, X., Qiu, S., 2023. Removal of ammonia nitrogen from aqueous media with low-cost adsorbents: a review. Water Air Soil Pollut. 234 (4), 280.

Ferrari, A., 2025. Animal bodies and futures: rethinking ethical implications of cultivated meat and fish. Food Ethics 10 (1), 6.

Fidder, L., Graça, J., 2023. Aligning cultivated meat with conventional meat consumption practices increases expected tastefulness, naturalness, and familiarity. Food Qual. Prefer. 109, 104911.

Fraeye, I., Kratka, M., Vandenburgh, H., Thorrez, L., 2020. Sensorial and nutritional aspects of cultured meat in comparison to traditional meat: much to be inferred. Front. Nutr. 7, 35.

Güney, O.I., Sangün, L., 2021. How COVID-19 affects individuals' food consumption behaviour: a consumer survey on attitudes and habits in Turkey. Br. Food J. 123 (7), 2307–2320.

Gerber, S., Bae, H., Ramirez, I., Cash, S.B., 2025. Publicly tasting cultivated meat and socially constructing perceived value politics and identity. npj Sci. Food 9 (1), 94.

González-Monroy, C., Gómez-Gómez, I., Olarte-Sánchez, C.M., Motrico, E., 2021. Eating behaviour changes during the COVID-19 pandemic: a systematic review of longitudinal studies. Int. j. environ. res. public health 18 (21), 11130.

Goswami, M., Belathur Shambhugowda, Y., Sathiyanarayanan, A., Pinto, N., Duscher, A., Ovissipour, R., Chandragiri Nagarajarao, R., 2022. Cellular aquaculture: prospects and challenges. Micromachines 13 (6), 828.

Goswami, M., Pinto, N., Yashwanth, B., Sathiyanarayanan, A., Ovissipour, R., 2023. Development of a cell line from skeletal trunk muscle of the fish Labeo rohita. Cytotechnology 75 (4), 349–361.

Gousset, C., Gregorio, E., Marais, B., Rusalen, A., Chriki, S., Hocquette, J.-F., Ellies-Oury, M.-P., 2022. Perception of cultured "meat" by French consumers according to their diet. Livest. Sci. 260, 104909.

Grzesik, P., Warth, S.C., 2021. One-time optimization of advanced T cell culture media using a machine learning pipeline. Front. bioeng. biotechnol. 9, 614324.

Hadi, J., Brightwell, G., 2021. Safety of alternative proteins: technological, environmental and regulatory aspects of cultured meat, plant-based meat, insect protein and single-cell protein. Foods 10 (6), 1226.

Hafeez, A., Shamair, Z., Shezad, N., Javed, F., Fazal, T., ur Rehman, S., Rehman, F., 2021. Solar powered decentralized water systems: a cleaner solution of the industrial wastewater treatment and clean drinking water supply challenges. J. Clean. Prod. 289, 125717.

Hanga, M.P., Ali, J., Moutsatsou, P., de la Raga, F.A., Hewitt, C.J., Nienow, A., Wall, I., 2020. Bioprocess development for scalable production of cultivated meat. Biotechnol. Bioeng. 117 (10), 3029–3039.

Haraguchi, Y., Okamoto, Y., Shimizu, T., 2022. A circular cell culture system using microalgae and mammalian myoblasts for the production of sustainable cultured meat. Arch. Microbiol. 204 (10), 615.

Haraguchi, Y., Shimizu, T., 2021. Microalgal culture in animal cell waste medium for sustainable 'cultured food'production. Arch. Microbiol. 203 (9), 5525–5532.

Hellung-Larsen, P., Andersen, A.P., 1989. Cell volume and dry weight of cultured Tetrahymena. J. Cell Sci. 92 (2), 319–324.

Hocquette, É., Liu, J., Ellies-Oury, M.-P., Chriki, S., Hocquette, J.-F., 2022. Does the future of meat in France depend on cultured muscle cells? Answers from different consumer segments. Meat sci. 188, 108776.

Hocquette, J.-F., Chriki, S., Fournier, D., Ellies-Oury, M.-P., 2025. Will "cultured meat" transform our food system towards more sustainability? Animal 19, 101145.

Huang, X., Wang, P., Xue, W., Cheng, J., Yang, F., Yu, D., Shi, Y., 2023. Preparation of meaty flavor additive from soybean meal through the Maillard reaction. Food Chem.: X 19, 100780.

Hubalek, S., Post, M.J., Moutsatsou, P., 2022. Towards resource-efficient and cost-efficient cultured meat. Curr. Opin. Food Sci. 47, 100885.

Humbird, D., 2021. Scale-up economics for cultured meat. Biotechnol. Bioeng. 118 (8), 3239–3250.

Jacobs, A.-K., Windhorst, H.-W., Gickel, J., Chriki, S., Hocquette, J.-F., Ellies-Oury, M.-P., 2024. German consumers' attitudes toward artificial meat. Front. Nutr. 11, 1401715.

Joo, S.-T., Choi, J.-S., Hur, S.-J., Kim, G.-D., Kim, C.-J., Lee, E.-Y., Hwang, Y.-H., 2022. A comparative study on the taste characteristics of satellite cell cultured meat derived from chicken and cattle muscles. Food Sci. Anim. Resour. 42 (1), 175.

Kaliji, S.A., Pakseresht, A., Hocquette, J.-F., 2025. Can blockchain revolutionize meat production? Addressing transparency, trust, and compliance in conventional and cultured meat. Trends in food science & technology, 105197.

Kawecki, N.S., Chen, K.K., Smith, C.S., Xie, Q., Cohen, J.M., Rowat, A.C., 2024. Scalable processes for culturing meat using edible scaffolds. Annu. Rev. Food Sci. Technol. 15.

Kim, C.-J., Kim, S.-H., Lee, E.-Y., Son, Y.-M., Bakhsh, A., Hwang, Y.-H., Joo, S.-T., 2023. Optimal temperature for culturing chicken satellite cells to enhance production yield and umami intensity of cultured meat. Food Chem. Adv. 2, 100307.

Kinoshita, M., Kobayashi, T., Planells, B., Klisch, D., Spindlow, D., Masaki, H., Uchikura, A., 2021. Pluripotent stem cells related to embryonic disc exhibit common

self-renewal requirements in diverse livestock species. Development 148 (23), dev199901.
Kirsch, M., Morales-Dalmau, J., Lavrentieva, A., 2023. Cultivated meat manufacturing: technology, trends, and challenges. Eng. Life Sci. 23 (12), e2300227.
Koh, B., Sulaiman, N., Fauzi, M.B., Law, J.X., Ng, M.H., Idrus, R.B.H., Yazid, M.D., 2020. Three dimensional microcarrier system in mesenchymal stem cell culture: a systematic review. Cell Biosci. 10, 1–16.
Kolodkin-Gal, I., Dash, O., Rak, R., 2023. Probiotic cultivated meat: bacterial-based scaffolds and products to improve cultivated meat. Trends Biotechnol.
Kossmann, H., Moess, T., Breunig, P., 2025. The climate impact and land use of cultivated meat: evaluating agricultural feedstock production. PloS one 20 (1), e0316480.
Krasnyanskyy, M., 2025. Advanced Technologies for Humanity's Adaptation to a Changing Climate. Authorea Preprints.
Krings, V.C., Dhont, K., Hodson, G., 2022. Food technology neophobia as a psychological barrier to clean meat acceptance. Food Qual. Prefer. 96, 104409.
Lee, M., Choi, W., Lee, J.M., Lee, S.T., Koh, W.-G., Hong, J., 2024. Flavor-switchable scaffold for cultured meat with enhanced aromatic properties. Nat. Commun. 15 (1), 5450.
Lembong, J., Kirian, R., Takacs, J.D., Olsen, T.R., Lock, L.T., Rowley, J.A., Ahsan, T., 2020. Bioreactor parameters for microcarrier-based human MSC expansion under xeno-free conditions in a vertical-wheel system. Bioengineering 7 (3), 73.
Leonardo, S., Toldrà, A., Campàs, M., 2021. Biosensors based on isothermal DNA amplification for bacterial detection in food safety and environmental monitoring. Sensors 21 (2), 602.
Letcher, S.M., Calkins, O.P., Clausi, H.J., McCreary, A., Trimmer, B.A., Kaplan, D.L., 2025. Establishment & characterization of a non-adherent insect cell line for cultivated meat. Sci. Rep. 15 (1), 7850.
Levenberg, S., Rouwkema, J., Macdonald, M., Garfein, E.S., Kohane, D.S., Darland, D.C., D'Amore, P.A., 2005. Engineering vascularized skeletal muscle tissue. Nat. Biotechnol. 23 (7), 879–884.
Lim, P.Y., Suntornnond, R., Choudhury, D., 2025. The nutritional paradigm of cultivated meat: bridging science and sustainability. Trends Food Sci. Technol. 156, 104838.
Liu, J., Almeida, J.M., Rampado, N., Panea, B., Hocquette, É., Chriki, S., Hocquette, J.-F., 2023. Perception of cultured "meat" by Italian, Portuguese and Spanish consumers. Front. Nutr. 10, 1043618.
Liu, J., Hocquette, É., Ellies-Oury, M.-P., Chriki, S., Hocquette, J.-F., 2021. Chinese consumers' attitudes and potential acceptance toward artificial meat. Foods 10 (2), 353.
Lowrey, J., Armenta, R.E., Brooks, M.S., 2016. Nutrient and media recycling in heterotrophic microalgae cultures. Appl. Microbiol. Biotechnol. 100, 1061–1075.
Maharjan, S., Yamashita, C., Lee, C.P., Villalobos Zepeda, A., Michel Farias, A.K., Duarte Rivera, A., Hernandez Medina, D.H., 2025. 3D bioprinting of plant and animal cell-based hybrid food. Nat. Commun. 16 (1), 6935.
Mahmood, A., Ali, S., 2017. Microbial and viral contamination of animal and stem cell cultures: common contaminants, detection and elimination. J. Stem Cell Res. Ther 2 (5), 1–8.
Mantzouridou, F.T., Paraskevopoulou, A., Lalou, S., 2015. Yeast flavour production by solid state fermentation of orange peel waste. Biochem. Eng. J. 101, 1–8.
Mariano Jr, E., Choi, Y., Park, J.M., Han, D., Kim, J.S., Park, J.W., Venter, C., 2025. Environmental impact of meat protein substitutes: A mini-review. Food sci. Anim. Resour. 45 (1), 62.
Mariano Jr, E., Lee, J., Choi, Y., Park, J., Han, D., Kim, J.S., Hur, S.J., 2024. A review on the characterization of edible scaffolds for cultured meat: physical, chemical, biocompatibility, and food safety evaluation methods. Food Chem., 142493
Marques, M.P., Szita, N., 2017. Bioprocess microfluidics: applying microfluidic devices for bioprocessing. Curr. Opin. Chem. Eng. 18, 61–68.
Mendes, G., Biscarra-Bellio, J.C., Heidemann, M.S., Taconeli, C.A., Molento, C.F.M., 2025. How much do opinions regarding cultivated meat vary within the same country? The cases of São Paulo and Salvador. Braz., PloS one 20 (2), e0317956.
Mihic, A., Li, J., Miyagi, Y., Gagliardi, M., Li, S.-H., Zu, J., Li, R.-K., 2014. The effect of cyclic stretch on maturation and 3D tissue formation of human embryonic stem cell-derived cardiomyocytes. Biomaterials 35 (9), 2798–2808.
Min, H., Cho, N.-J., 2024. Waste management for environmentally sustainable cities: A quadruple helix collaboration in practice. ACS Sustain. Resour. Manag. 1 (8), 1620–1629.
Miyamoto, S., Hirakawa, T., Noguchi, Y., Urushiyama, D., Miyata, K., Baba, T., Hata, K., 2023. Physical properties of ultrafine bubbles generated using a generator system. in vivo 37 (6), 2555–2563.
Morishita, R., Itoh, S., Takeda-Morishita, M., 2022. Evaluation of bactericidal effects of H2-and O3-filled ultrafine bubbles water. Biocontrol Sci. 27 (3), 139–142.
Mottet, A., de Haan, C., Falcucci, A., Tempio, G., Opio, C., Gerber, P., 2017. Livestock: on our plates or eating at our table? A new analysis of the feed/food debate. Glob. Food Secur. 14, 1–8.
Mukherjee, K., Trieb, J., Niegowska Conforti, M., Di Martino, M., Fattori, V., Lipp, M., 2025. Explor. future landsc. new food sources prod. syst.
Negulescu, P.G., Risner, D., Spang, E.S., Sumner, D., Block, D., Nandi, S., McDonald, K. A., 2023. Techno-economic modeling and assessment of cultivated meat: impact of production bioreactor scale. Biotechnol. Bioeng. 120 (4), 1055–1067.
Ng, W.L., Tan, J.S., 2024. Application of machine learning in 3D bioprinting of cultivated meat. Int. J. AI Mater. Des 1, 2279.
Ng, W.L., Tan, J.S., 2025. Machine learning in cultivated meat: enhancing sustainability, efficiency, quality, and scalability across the production pipeline. Food Bioprocess Technol. 1–22.
Nikkhah, A., Rohani, A., Zarei, M., Kulkarni, A., Batarseh, F.A., Blackstone, N.T., Ovissipour, R., 2023. Toward sustainable culture media: using artificial intelligence to optimize reduced-serum formulations for cultivated meat. Sci. Total Environ. 894, 164988.
Noguchi, T., Ebina, K., Hirao, M., Morimoto, T., Koizumi, K., Kitaguchi, K., Yoshikawa, H., 2017. Oxygen ultra-fine bubbles water administration prevents bone loss of glucocorticoid-induced osteoporosis in mice by suppressing osteoclast differentiation. Osteoporos. Int. 28, 1063–1075.
O'Neill, E.N., Cosenza, Z.A., Baar, K., Block, D.E., 2021. Considerations for the development of cost-effective cell culture media for cultivated meat production. Compr. Rev. Food Sci. Food Saf. 20 (1), 686–709.
Ogawa, M., Kermani, A.S., Huynh, M.J., Baar, K., Leach, J.K., Block, D.E., 2024. Edible mycelium as proliferation and differentiation support for anchorage-dependent animal cells in cultivated meat production. npj Sci. Food 8 (1), 23.
Olenic, M., Thorrez, L., 2023. Cultured meat production: what we know, what we don't know and what we should know. Ital. J. Anim. Sci. 22 (1), 749–753.
Ong, K.J., Johnston, J., Datar, I., Sewalt, V., Holmes, D., Shatkin, J.A., 2021. Food safety considerations and research priorities for the cultured meat and seafood industry. Compr. Rev. Food Sci. Food Saf. 20 (6), 5421–5448.
Organization, W. H., 2023. Food safety aspects of cell-based food. World Health Organization.
Ornelas-González, A., González-González, M., Rito-Palomares, M., 2021. Microcarrier-based stem cell bioprocessing: GMP-grade culture challenges and future trends for regenerative medicine. Crit. Rev. Biotechnol. 41 (7), 1081–1095.
Østergaard, P.A., Duic, N., Noorollahi, Y., Mikulcic, H., Kalogirou, S., 2020. Sustainable development using renewable energy technology. Elsevier, pp. 2430–2437. Vol. 146.
Pajčin, I., Knežić, T., Savic Azoulay, I., Vlajkov, V., Djisalov, M., Janjušević, L., Gadjanski, I., 2022. Bioengineering outlook on cultivated meat production. Micromachines 13 (3), 402.
Pakbin, B., Amanipour, A., Amirvaresi, A., Shahsavari, A., Ovissipour, R., 2025. Development and optimization of the ammonia removal strategy for sustainable recycling of cell culture spent Media in cultivated meat production; from concept to implementation. Front. Bioeng. Biotechnol. 13, 1617115.
Pakseresht, A., Kaliji, S.A., Canavari, M., 2022. Review of factors affecting consumer acceptance of cultured meat. Appetite 170, 105829.
Pareti, M., Guo, J., Yin, J., Liu, Q., Abudurofu, N., Bulibuli, A., Canavari, M., 2025. Exploring Chinese consumers' Perception and potential acceptance of cell-cultured meat and plant-based meat: A focus group study and content analysis. Foods 14 (9), 1446.
Park, Y., Shin, S., Shukla, N., Kim, K., Park, M.-H., 2022. Effects of nanobubbles in dermal delivery of drugs and cosmetics. Nanomaterials 12 (19), 3286.
Pasitka, L., Cohen, M., Ehrlich, A., Gildor, B., Reuveni, E., Ayyash, M., Niv, A., 2023. Spontaneous immortalization of chicken fibroblasts generates stable, high-yield cell lines for serum-free production of cultured meat. Nat. Food 4 (1), 35–50.
Perreault, L.R., Thyden, R., Kloster, J., Jones, J.D., Nunes, J., Patmanidis, A.A., Gaudette, G.R., 2023. Repurposing agricultural waste as low-cost cultured meat scaffolds. Front. Food Sci. Technol. 3, 1208298.
Peter, A.P., Koyande, A.K., Chew, K.W., Ho, S.-H., Chen, W.-H., Chang, J.-S., Show, P.L., 2022. Continuous cultivation of microalgae in photobioreactors as a source of renewable energy: current status and future challenges. Renew. Sustain. Energy Rev. 154, 111852.
Peyraud, J.-L., Hocquette, J.-F., 2025. Towards a balanced view of livestock: benefits of grazing farming systems to produce meat. Livest. Sci., 105829
Piantino, M., Muller, Q., Nakadozono, C., Yamada, A., Matsusaki, M., 2025. Towards more realistic cultivated meat by rethinking bioengineering approaches. Trends Biotechnol. 43 (2), 364–382.
Podolinnaia, V., Kameda, T., Takanashi, I., Kitagawa, F., Kumagai, S., Saito, Y., Yoshioka, T., 2023. Adsorption of l-lactate from cell culture media by layered double hydroxide and evaluation of its cytotoxicity to cell lines. JCIS Open 12, 100099.
Powell, D.J., Li, D., Smith, B., Chen, W.N., 2025. Cultivated meat microbiological safety considerations and practices. Compr. Rev. Food Sci. Food Saf. 24 (1), e70077.
Qu, X., Qi, P., Wang, P., Li, J., Wang, C., Zhang, D., Wang, X., 2023. A self-powered biosensing system based on triboelectric nanogenerator for rapid bacterial DNA detection. Sens. Actuators B: Chem. 390, 133917.
Ramani, S., Ko, D., Kim, B., Cho, C., Kim, W., Jo, C., Park, S., 2021. Technical requirements for cultured meat production: a review. J. Anim. Sci. Technol. 63 (4), 681.
Rao, K.M., Choi, S.M., Han, S.S., 2023. A review on directional muscle cell growth in scaffolding biomaterials with aligned porous structures for cultivated meat production. Food Res. Int. 168, 112755.
Reiss, J., Robertson, S., Suzuki, M., 2021. Cell sources for cultivated meat: applications and considerations throughout the production workflow. Int. J. Mol. Sci. 22 (14), 7513.
Rodríguez Escobar, M.I., Cadena, E., Nhu, T.T., Cooreman-Algoed, M., De Smet, S., Dewulf, J., 2021. Analysis of the cultured meat production system in function of its environmental footprint: current status, gaps and recommendations. Foods 10 (12), 2941.
Rowley, J., Abraham, E., Campbell, A., Brandwein, H., Oh, S., 2012. Meeting lot-size challenges of manufacturing adherent cells for therapy. BioProcess Int 10 (3), 7.
Roxburgh, N., Burton, R.J., Mittenzwei, K., Polhill, J.G., 2025. Modelling the effect of a carbon tax on the development of a cultivated protein industry: a Norwegian case study. Cleaner Engineering and Technology, 100979.
Saad, M.K., Yuen Jr, J.S., Joyce, C.M., Li, X., Lim, T., Wolfson, T.L., Calkins, O.P., 2023. Continuous fish muscle cell line with capacity for myogenic and adipogenic-like phenotypes. Sci. Rep. 13 (1), 5098.
Samad, A., Kim, S., Kim, C.J., Lee, E.-Y., Kumari, S., Hossain, M.J., Hwang, Y.-H., 2024. Revolutionizing cell-based protein: innovations, market dynamics, and future prospects in the cultivated meat industry. J. Agric. Food Res. 18, 101345.

Santos, A.C.A., Camarena, D.E.M., Roncoli Reigado, G., Chambergo, F.S., Nunes, V.A., Trindade, M.A., Stuchi Maria-Engler, S., 2023. Tissue engineering challenges for cultivated meat to meet the real demand of a global market. Int. J. Mol. Sci. 24 (7), 6033.

Santos, A.E.A.d., Guadalupe, J.L., Albergaria, J.D.S., Almeida, I.A., Moreira, A.M.S., Copola, A.G.L., Santos, J.P.F., 2024. Random cellulose acetate nanofibers: a breakthrough for cultivated meat production. Front. Nutr. 10, 1297926.

Schinn, S.M., Morrison, C., Wei, W., Zhang, L., Lewis, N.E., 2021. A genome-scale metabolic network model and machine learning predict amino acid concentrations in Chinese hamster ovary cell cultures. Biotechnol. Bioeng. 118 (5), 2118–2123.

Schwarz, H., Lee, K., Castan, A., Chotteau, V., 2023. Optimization of medium with perfusion microbioreactors for high density CHO cell cultures at very low renewal rate aided by design of experiments. Biotechnol. Bioeng. 120 (9), 2523–2541.

Shaw, E., Mac Con Iomaire, M., 2019. A comparative analysis of the attitudes of rural and urban consumers towards cultured meat. Br. Food J. 121 (8), 1782–1800.

Shimizu, T., Okamoto, Y., Tanaka, R.-i., Sakaguchi, K., Kikuchi, T., Haraguchi, Y., 2021. Circular food production system using algae/animal cell recycling culture. In: 50th International Conference on Environmental Systems.

Silbergeld, E.K., Graham, J., Price, L.B., 2008. Industrial food animal production, antimicrobial resistance, and human health. Annu. Rev. Public Health 29 (1), 151–169.

Singh, A., Kumar, S., 2025. Exploring the functionality of microbes in fermented foods: technological advancements and future directions. Fermentation 11 (6), 300.

Sinke, P., Swartz, E., Sanctorum, H., van der Giesen, C., Odegard, I., 2023. Ex-ante life cycle assessment of commercial-scale cultivated meat production in 2030. Int. J. Life Cycle Assess. 28 (3), 234–254.

Skorbiansky, S.R., McFadden, J., Saavoss, M., 2024. The Economics of Cellular Agriculture. US Department of Agriculture, Economic Research Service.

Specht, E.A., Welch, D.R., Clayton, E.M.R., Lagally, C.D., 2018. Opportunities for applying biomedical production and manufacturing methods to the development of the clean meat industry. Biochem. Eng. J. 132, 161–168.

Srutee, R., Sowmya, R., Annapure, U.S., 2022. Clean meat: techniques for meat production and its upcoming challenges. Anim. Biotechnol. 33 (7), 1721–1729.

Starowicz, M., Poznar, K.K., Zieliński, H., 2022. What are the main sensory attributes that determine the acceptance of meat alternatives? Curr. Opin. Food Sci. 48, 100924.

Stern Bauer, T., Yakobi, R., Hurevich, M., Yitzchaik, S., Hayouka, Z., 2023. Impedimetric bacterial detection using random antimicrobial peptide mixtures. Sensors 23 (2), 561.

Sugii, S., Wong, C.Y.Q., Lwin, A.K.O., Chew, L.J.M., 2022. Reassessment of adipocyte technology for cellular agriculture of alternative fat. Compr. Rev. Food Sci. Food Saf. 21 (5), 4146–4163.

Sun, W., Tang, H., Wang, L., Du, G., Zhou, J., Chen, J., Guan, X., 2025. Rational scaling-up strategy for cultured meat production based on bioreactor micro-environment evaluation. Food Biosci. 63, 105737.

Szejda, K., Bryant, C.J., Urbanovich, T., 2021. US and UK consumer adoption of cultivated meat: a segmentation study. Foods 10 (5), 1050.

Takahashi, K., Yamanaka, S., 2016. A decade of transcription factor-mediated reprogramming to pluripotency. Nat. rev. Mol. cell biol. 17 (3), 183–193.

Tavan, M., Smith, N.W., McNabb, W.C., Wood, P., 2025. Reassessing the sustainability promise of cultured meat: a critical review with new data perspectives. Crit. Rev. Food Sci. Nutr. 1–9.

To, K., Comer, C.C., O'Keefe, S.F., Lahne, J., 2024. A taste of cell-cultured meat: a scoping review. Front. Nutr. 11, 1332765.

Tran, N.L.H., Lam, T.Q., Duong, P.V.Q., Doan, L.H., Vu, M.P., Nguyen, K.H.P., Nguyen, K. T., 2023. Review on the significant interactions between ultrafine gas bubbles and biological systems. Langmuir 40 (1), 984–996.

Tuomisto, H.L., Teixeira de Mattos, M.J., 2011. Environmental impacts of cultured meat production. Environ. Sci. Technol. 45 (14), 6117–6123.

Ulagesan, S., Krishnan, S., Nam, T.-J., Choi, Y.-H., 2025. Development and characterization of red seabream (Pagrus major) muscle satellite cell lines for cultivated seafood: highlighting serum reduction and microcarrier expansion: S. Ulagesan et al. In Vitro Cell. Dev. Biol.-Anim. 1–14.

Van Boeckel, T.P., Pires, J., Silvester, R., Zhao, C., Song, J., Criscuolo, N.G., Laxminarayan, R., 2019. Global trends in antimicrobial resistance in animals in low- and middle-income countries. Science 365 (6459), eaaw1944.

Wang, L., Li, G., Li, X., Zhang, Y., Liu, G., Xie, M., Kaplan, D.L., 2025. Emerging materials in cultivated meat: engineering sustainable food Solutions–A review. Adv. Funct. Mater. 35 (3), 2413316.

Wells, V., Carrigan, M., Athwal, N., 2023. Pandemic-driven consumer behaviour: A foraging exploration. Mark. Theory 23 (4), 631–659.

Wimble, J., Ashizawa, R., Swartz, E.W., 2025. Analysis of the economic viability and environmental impacts of a conceptual process for the recovery of lactic acid from spent media in cultivated meat production. bioRxiv, 2025.2004. 2030.651479.

Wood, P., Thorrez, L., Hocquette, J.-F., Troy, D., Gagaoua, M., 2023. Cellular agriculture": current gaps between facts and claims regarding "cell-based meat. Anim. Front. 13 (2), 68–74.

Wu, M., Ahmadian Yazdi, A., Attinger, D., Xu, J., 2020. Energy-harvesting bioreactors: toward self-powered microfluidic devices, a mini-review. Microfluid. Nanofluidics 24, 1–9.

Xu, W., Jin, T., Dai, Y., Liu, C.C., 2020. Surpassing the detection limit and accuracy of the electrochemical DNA sensor through the application of CRISPR Cas systems. Biosens. Bioelectron. 155, 112100.

Xuan, Z., Peng, Q., Borsuk, M., Prasad, R., Zachar, V., Das, S.K., Pennisi, C.P., 2025. Dev. sustain. strategy cult. fat prod. based serum-free 3D cult. bov. adipose stem cells.

Yakir, I., Cohen, E., Schlesinger, S., Hayouka, Z., 2025. Random antimicrobial peptide mixtures as non-antibiotic antimicrobial agents for cultured meat industry. Food Chem.: Molecular Sci. 10, 100240.

Yang, M., Wang, Q., Zhu, Y., Sheng, K., Xiang, N., Zhang, X., 2023. Cell culture medium cycling in cultured meat: key factors and potential strategies. Trends in food science & technology.

Yuen Jr, J.S.K., Saad, M.K., Xiang, N., Barrick, B.M., DiCindio, H., Li, C., Zhang, K.L., 2023. Aggregating in vitro-grown adipocytes to produce macroscale cell-cultured fat tissue with tunable lipid compositions for food applications. Elife 12, e82120.

Zhang, L., Guo, W., Lv, C., Liu, X., Yang, M., Guo, M., Fu, Q., 2023. Electrochemical biosensors represent promising detection tools in medical field. Advanced Sensor and Energy Materials, 100081.

Zhang, Y., Hu, X., Wang, Q., Zhang, Y., 2022. Recent advances in microchip-based methods for the detection of pathogenic bacteria. Chin. Chem. Lett. 33 (6), 2817–2831.

Zhou, J., Yin, L., Dong, Y., Peng, L., Liu, G., Man, S., Ma, L., 2020. CRISPR-Cas13a based bacterial detection platform: sensing pathogen Staphylococcus aureus in food samples. Anal. Chim. Acta 1127, 225–233.

Zhou, X., Zheng, H., Wu, Y., Yin, H., Mao, X., Li, N., Ai, Q., 2025. Scalable production of muscle and adipose cell-laden microtissues using edible macroporous microcarriers for 3D printing of cultured fish fillets. Nat. Commun. 16 (1), 1740.