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Review

Cultured meat: advances in stem cell biology, tissue engineering, and bioprocess optimisation for scalable and sustainable production—a review

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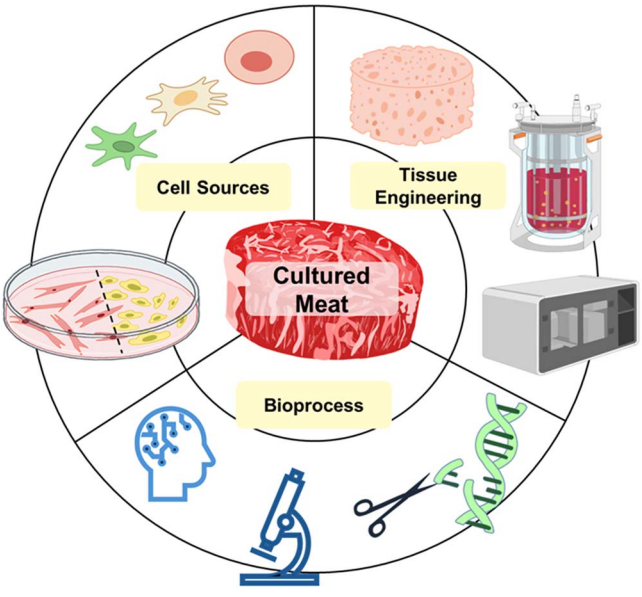
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Abstract

Cultured meat represents an emerging technology with the potential to address global food security and sustainability challenges by producing animal-derived meat without slaughter. Unlike plant-based alternatives, it replicates the biological and sensory properties of conventional meat through controlled cell cultivation. This review provides an integrated overview of recent advances in cell line development, differentiation strategies, scaffold engineering, bioreactor design, and media optimisation for scalable cultured meat production. It also examines critical challenges related to cost reduction, automation, and process control, as well as consumer acceptance and regulatory readiness. By combining progress in stem cell biology, tissue engineering, and bioprocessing, this review highlights the translational pathway of cultured meat development—from the laboratory bench to the dining table—emphasising its multidisciplinary nature and potential for sustainable commercialisation.

Keywords: cultured meat, stem cell biology, tissue engineering, bioprocess optimisation, bench to dining table

Graphical abstract



Introduction

The anticipated growth of the world population to 9.7 billion people by the year 2050 poses a serious risk to food systems and environmental sustainability (Gerland et al., 2014). Various studies have indicated that current food systems will be challenging to manage in a way that provides adequate nutrition for all and is environmentally sustainable (Fanzo et al., 2022). The livestock

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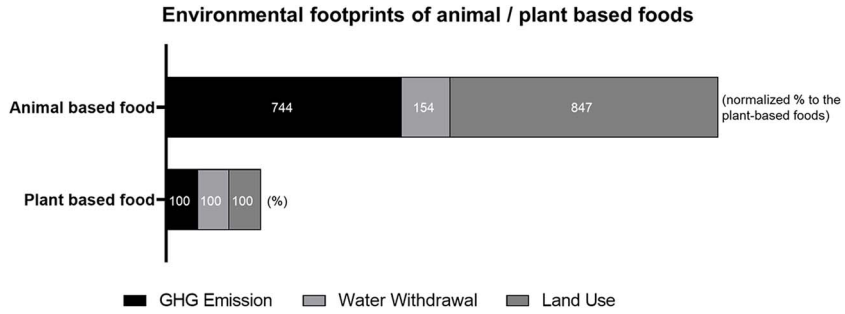


Figure 1. Environmental and resource impacts of livestock production, environmental footprints linked to the production of different food categories. The figure compares greenhouse gas (GHG) emissions, land use, and freshwater withdrawal for animal-based and plant-based food groups. Each indicator is expressed relative to the plant-based food category, which acts as the baseline for normalisation. Higher values indicate a greater environmental impact. Animal-derived products such as beef and pork show significantly higher footprints across all three parameters, emphasising the environmental burden of conventional livestock farming compared to plant-based alternatives.

industry is one of the leading causes of deforestation, and its activities contribute around 14.5% of greenhouse gas (GHG) emissions, with methane having the highest emission potential (Gerber et al., 2013).

Traditional livestock production is highly capital- and resource-intensive. While it provides less than 20% of the world's calorie supply, it occupies approximately 77% of global agricultural land. Considering that only about 71% of the Earth's surface is habitable and roughly 50% of that is used for agriculture, livestock farming accounts for around 27.3% of all habitable land (Gerber et al., 2013). Furthermore, in terms of environmental impact, animal-based foods have disproportionately higher carbon footprints than plant-based alternatives. Specifically, their GHG emissions, land use, and freshwater consumption are approximately 744%, 847%, and 154% higher, respectively, than those of plant-based foods (Figure 1) (FAO, 2020; Poore & Nemecek, 2018).

Beyond addressing environmental concerns, cultured meat also provides several key advantages over traditional livestock production. First, it offers an ethical solution by eliminating the need for animal slaughter, as meat can be produced indefinitely from cells obtained through minimally invasive biopsies (Bhat et al., 2019). Second, cultured meat production is largely unaffected by external factors, such as weather or feed availability, enabling planned and large-scale manufacturing under controlled conditions that ensure a stable and predictable food supply (Chriki & Hocquette, 2020). Third, it avoids many of the public health issues associated with conventional animal farming, including the overuse of antibiotics and hormones that contribute to antimicrobial resistance and pose long-term health risks (O'Neill, 2016). Collectively, these advantages highlight the necessity and timeliness of cultured meat as a sustainable and ethical alternative to conventional meat production.

In response to these challenges, cultured meat—also referred to as lab-grown, cultivated, or cell-based meat—has emerged as a promising alternative. Produced by cultivating animal cells in vitro, this technology aims to replicate the structure, taste, and nutritional value of conventional meat without the need for animal slaughter (Bhat et al., 2015). Recent advances in stem cell biology, tissue engineering, and bioprocessing technologies have driven significant progress in cultured meat research and development (MacQueen et al., 2019). Despite this promise, significant social, financial, and scientific obstacles remain for cultured meat. These include the creation of scalable bioreactor systems, the selection and modification of suitable cell lines, the creation of culture media devoid of serum, and the engineering of edible scaffolds that replicate the texture of natural meat (Riquelme-Guzmán et al., 2024). Furthermore, market positioning, regulatory approval, and public acceptance continue to be important determinants of the feasibility of commercial production (Siegrist & Hartmann, 2020).

To provide a thorough overview of the most recent advancements in cultured meat production, this review will focus on stem cell technologies, differentiation strategies, biomaterials and scaffolding, and bioreactor design. Additionally, we highlight new developments in consumer perception and regulatory obstacles, underscoring the significance of interdisciplinary efforts in the commercialisation of cultured meat. Ultimately, this review follows the bench-to-dining table trajectory of cultured meat, bridging fundamental cellular research with industrial bioprocessing and consumer-level applications.

Cell sources and differentiation strategies

Selection of cell lines

Deciding on the source of a cell line is arguably the most critical factor in the production of cultured meat, as the species origin of the cells significantly influences their ability to proliferate and differentiate, in addition to affecting the overall quality of the meat produced (Kadim et al., 2015). Ideally, the chosen cell line should possess excellent proliferation capabilities, a strong potential for differentiation into both muscle and adipose tissue, and a stable genome to ensure consistent industrial-scale production (Ben-Arye & Levenberg, 2019). Extensive research has been conducted on various cell types, including satellite cells, mesenchymal stem cells (MSCs), and induced pluripotent stem cells (iPSCs), to assess their suitability for cultured meat applications (Table 1). Because different cells function independently, it is essential to develop new culture systems and engineering approaches to optimise their effectiveness (Verbruggen et al., 2018). The overall workflow of cultured meat manufacturing, from cell isolation to tissue assembly, is schematically summarised in Figure 2.

Satellite cells: the gold standard for muscle formation

Satellite cells, the stem cells of adult skeletal muscle tissue, play a crucial role in muscle repair and regeneration (Zhu & Peek, 2024). These cells are located between the basal lamina and the sarcolemma of muscle fibres (Fu et al., 2015). They remain quiescent until triggered by factors such as injury, exercise, or growth (Brett et al., 2020). Upon activation, satellite cells begin to proliferate and differentiate into myoblasts, which subsequently fuse to form multinucleated myotubes—the fundamental components of muscle tissue. Due to their myogenic potential, satellite

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Table 1. Comparison of major cell sources for cultured meat production, comparison of major cell sources for cultured meat production, including satellite cells, immortalised satellite cells, mesenchymal stem cells (MSCs), and induced pluripotent stem cells (iPSCs). Each cell type is evaluated according to its biological origin, key functional characteristics, and differentiation potential. The table summarises their primary advantages, such as proliferative capacity and myogenic or adipogenic competence, their inherent limitations, including senescence, genomic instability, and ethical concerns, and representative optimisation strategies—such as hypoxic culture, feeder-layer systems, or CRISPR-based regulation—that are currently employed to enhance scalability and safety for industrial application. MRF, myogenic regulatory factors; TERT, telomerase reverse transcriptase.

Cell source	Origin and characteristics	Advantages	Limitations	Optimisation strategies
Satellite cells	– Adult stem cells located beneath the basement membrane – Remain quiescent until activated by injury, exercise, or growth –Differentiate into myotubes *via* MRFs (MyoD, Myf5, MyoG, MRF4)	–Specialised for muscle formation and regeneration – Strong myogenic lineage commitment	– Rapid senescence – Limited proliferative capacity	– Feeder-layer-based culture system – Hypoxic culture conditions
Immortalised satellite cells	– Derived from satellite cells – Genetically modified *via* TERT overexpression and p53 suppression – Designed to improve longevity while maintaining myogenic potential	– High proliferation capacity – Suitable for long-term expansion and large-scale production	– Effective adipogenic differentiation – Enable intramuscular fat (marbling) formation	– High proliferation capacity – Theoretically unlimited supply of cells – Provides a sustainable source for large-scale production
Mesenchymal stem cells (MSCs)	– Isolated from adipose tissue and other adult tissues – Exhibit both adipogenic and myogenic differentiation potential	– Genetic modification may raise concerns regarding consumer acceptance	– Lower efficiency in myogenic differentiation compared to satellite cells	– Tumorigenicity – Genetic instability
Induced pluripotent stem cells (iPSCs)	– Reprogrammed from somatic cells – Pluripotent and capable of unlimited proliferation	– Genetic engineering (e.g., TERT or TP53 deletion)	– Mechanical stimulation – Scaffold stiffness modulation – Chemical induction – Co-culture with myogenic cells	– Treatment with CHIR99021 and FGF-2 – Pax7-mediated induction of satellite-like cells – Integration-free reprogramming systems – CRISPR-based gene regulation

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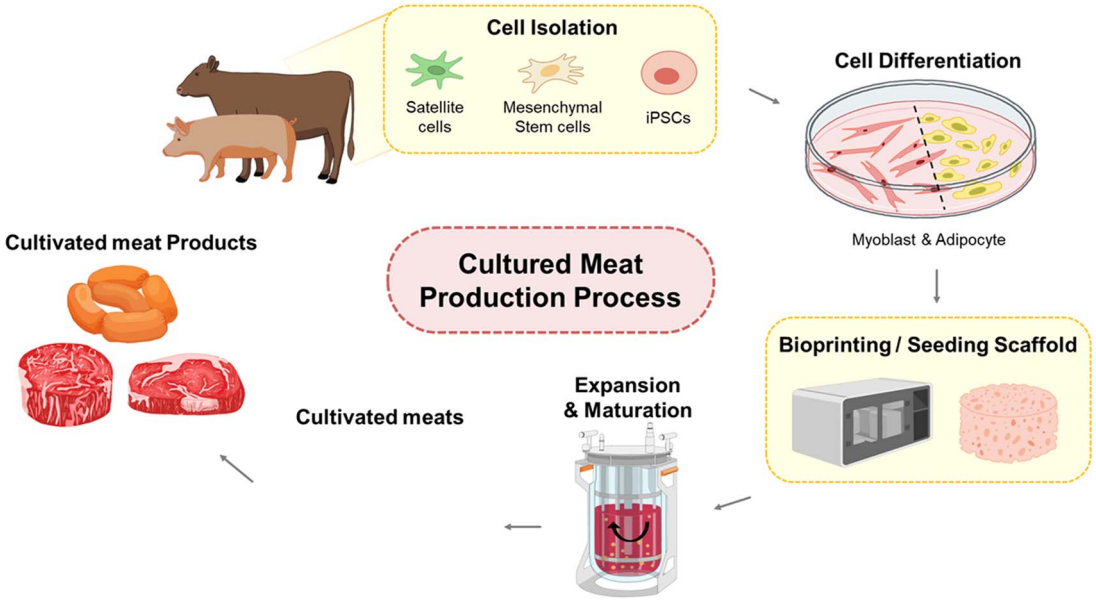


Figure 2. Schematic of cultured meat production process, schematic overview of the stepwise process for cultured meat production. The workflow begins with the isolation of stem cells or muscle progenitor cells from donor animals through minimally invasive biopsies. The isolated cells are differentiated into myogenic and adipogenic lineages under optimised in vitro conditions. Differentiated cells are then expanded and assembled into three-dimensional (3D) tissue constructs using scaffolds or 3D bioprinting techniques. The constructs undergo further maturation in bioreactors, where mechanical and biochemical cues promote alignment and functional development of muscle fibres. The matured tissues form cultivated meat, which is subsequently processed into the final meat product ready for consumption. Arrows indicate the sequential integration of biological and engineering stages across the production pipeline.

cells are considered prime candidates for the production of cultured meat (Dhawan & Rando, 2005). They also possess myogenic regulatory factors (MRFs), such as MyoD, Myf5, myogenin (MyoG), and MRF4, all of which are essential for muscle fibre development. However, satellite cells have limitations, including a restricted capacity for proliferation (Yin et al., 2013). They reach replicative senescence after a limited number of cell divisions (Sousa-Victor et al., 2015), thus posing challenges for cultured meat production, which requires continuous cell division and expansion (Stephens et al., 2018).

Several strategies have been developed to overcome these limitations. The use of genetic engineering, specifically the insertion of telomerase reverse transcriptase (TERT) or the deletion of p53, has the potential to improve satellite cell longevity while preserving their differentiation capabilities. Strategies for the expansion of stem cells in bioreactors, which include low oxygen levels (hypoxia) and mechanical vibrations, have been shown to promote satellite cell proliferation and prevent senescence (Powell et al., 2002). Additionally, maintaining the stemness of satellite cells in expansion cultures can be achieved by utilising feeder cell systems, such as fibroblast feeder layers or conditioned media from supportive cells (Conboy et al., 2003). Despite progress in these areas, the challenge of improving the efficiency and scalability of satellite cell production for practical application remains a primary focus for researchers. To address these challenges, recent research has shown that hypoxic conditions can promote satellite cell proliferation while inhibiting myogenic differentiation, indicating that oxygen tension is a crucial factor in developing scalable satellite cell culture systems (Jung et al., 2024).

MSCs: a versatile alternative

Mesenchymal stem cells possess the ability to differentiate into various cell types, including skeletal muscle, adipose tissue, connective tissues, and other mesodermal cells. These cells can be obtained from a variety of tissues, including bone marrow, adipose tissue, and Wharton's jelly found in umbilical cords (Baouche et al., 2023). Due to these characteristics, MSCs are emerging as a promising alternative to satellite cells in the cultured meat industry.

The capacity for further differentiation offers MSCs an advantage over satellite cells, allowing for prolonged differentiation in continuous culture without requiring an additional proliferation phase (Grobbelaar et al., 2024). Similar to other stem cells, MSCs have immunomodulatory capabilities, which contribute to their resistance against stress and senescence associated with the culture conditions (Le Blanc, 2006). However, a limitation is that the efficacy of muscle differentiation from MSCs is inferior to that of satellite cells, as satellite cells can undergo myogenesis due to their comparatively higher expression of MRFs (Almeida et al., 2016).

Various techniques have been established to enhance muscle formation from MSCs. The expression of myogenic markers, such as MyoD, Myf5, and myosin heavy chain (MyHC), can be induced in MSCs through cyclic stretching and electrical stimulation (Mishra et al., 2020). Myogenic differentiation can also be promoted by coculturing MSCs with satellite cells due to stimulation from the cellular microenvironment (Dezawa et al., 2005; Milner et al., 2018). Furthermore, myoblast-like cells can be formed by chemically transforming MSCs with small compounds, such as 6-bromoindirubin-3′-oxime (BIO), valproic acid, and all-*trans* retinoic acid (García-Guerrero et al., 2024).

Mesenchymal stem cells are also a valuable source for adipose tissue formation, as they can differentiate into adipose cells. Adipose tissue plays a crucial role in the texture and flavour of meat, as well as in muscle differentiation. The adipogenesis of MSCs is regulated by key transcription factors, including PPARγ, C/EBPα, and C/EBPβ, which collectively control lipid accumulation and fat cell maturation (Shao et al., 2024). Due to their potential

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to differentiate into both muscle and fat, MSCs are a promising option for co-culture approaches aimed at producing marbled meat (MacQueen et al., 2019). Nevertheless, batch-to-batch variability and other challenges, such as inconsistency between fat and muscle differentiation, hinder the widespread application of MSCs in the commercial production of cultured meat (Borys et al., 2021).

iPSCs: far-reaching capabilities for mass production

Induced pluripotent stem cells are obtained from somatic cells that possess the ability to self-renew and differentiate into various cell types, including muscle and adipose cells (Takahashi et al., 2007). Unlike satellite cells and MSCs, iPSCs are not limited by the source of the somatic cell, making them exceptionally useful for large-scale meat production. The differentiation of iPSCs into skeletal muscle cells usually requires directed differentiation procedures that simulate embryonic myogenesis (Chal & Pourquié, 2017). The small molecule CHIR99021, which activates Wnt signalling, is used in conjunction with fibroblast growth factor 2 (FGF-2) to drive the cells towards skeletal muscle lineage, providing a controlled level of induction (Kreuser et al., 2020). Efficient iPSC-to-myoblast differentiation is accomplished through molecular manipulations, including the activation of the muscle progenitor formation controlling gene, *Pax7* (Hicks et al., 2023). Furthermore, bioreactor-based differentiation utilising dynamic suspension culture systems enables large-scale cell differentiation while preserving cell function and viability.

Similarly, iPSCs can be transformed into adipocytes through the use of PPARγ agonists and insulin signal transduction, resulting in lipid-rich fat cells that effectively mimic the texture and taste of meat (Rosen & MacDougald, 2006). In a recent study, Recchia et al. (2025) demonstrated the potential of iPSC-derived muscle tissue for cultured meat applications by successfully reprogramming bovine fetal fibroblasts into iPSCs and inducing myogenic differentiation (Recchia et al., 2025). Nevertheless, their commercial utilisation for food applications remains on hold due to safety issues (O'Neill, 2016). The risk of tumorigenicity arising from chromosomal nondisjunction or genomic instability necessitates stringent quality control; however, some nonintegrating reprogramming methods may compromise these standards (Specht et al., 2018).

Modulation of gene expression is a generic approach that can address various safety concerns. For example, messenger RNA (mRNA)-based reprogramming avoids any genetic modifications and the associated safety risks. Additionally, the concept of protein-based mRNA capping employs the direct application of reprogramming factors, thereby minimising the risk of unintended consequences. Differentiation pathways can be precisely controlled through clustered regularly interspaced short palindromic repeats (CRISPR)-based gene regulation, which enables modulation without causing permanent genomic alterations (Wu et al., 2025). Although iPSCs offer remarkable versatility, their tumorigenic potential remains a major barrier to their use in food applications. This risk primarily arises from integration-based reprogramming methods (e.g., retroviral or lentiviral vectors) that can activate oncogenes or disrupt tumour suppressor genes, as well as from chromosomal abnormalities accumulated during long-term culture. To mitigate these concerns, nonintegrating reprogramming techniques have been developed that eliminate the need for viral DNA insertion. Among these, mRNA-based reprogramming enables the transient expression of key reprogramming factors (OCT4, SOX2, KLF4, and c-MYC) without genomic integration, thereby preventing insertional mutagenesis and maintaining genome integrity. In addition, protein-based mRNA capping employs synthetic cap analogues (e.g., anti-reverse cap analogues, ARCAs) and recombinant protein delivery systems to enhance translation efficiency and stability of reprogramming factors while minimising innate immune activation (Sahin et al., 2014; Warren et al., 2010). These improvements enable efficient induction of pluripotency with substantially reduced tumorigenic risk, representing a promising direction for the safe use of iPSCs in cultured meat production (Stephens et al., 2018).

Muscle and fat differentiation

To replicate the texture, structure, and nutritional qualities of conventional meat, stem cells must be accurately differentiated into muscle and fat tissues (Figure 3) (Kadim et al., 2015). The production of cultured meat requires a complex combination of mature muscle fibres and fat tissue to achieve the sensory attributes of tenderness, juiciness, and flavour (Bhat et al., 2015). The differentiation of stem or progenitor cells into specialised cell types is regulated by a complex interplay of genetic, biochemical, and mechanical signals that dictate the production of tissue-specific cell types (Ben-Arye & Levenberg, 2019).

Myogenic differentiation: mechanisms and strategies

Myogenesis is a highly regulated process that leads to the formation of muscle tissue, predominantly composed of myofibers containing multiple nuclei. Myogenic regulatory factors, such as MyoD, Myf5, MyoG, and MRF4, activate the differentiation of stem cells into muscle cells (Iberite et al., 2022). These transcription factors are essential for the development of muscle progenitor cells into mature myotubes (Sabourin & Rudnicki, 2000). MyoD, Myf5, and other MRFs play a critical role in generating the contractile and metabolic fibres of muscle by influencing the genes related to muscle development (Ma et al., 2024).

Another important factor in myogenic differentiation is the signalling from a specific Wnt pathway, which is vital for the proliferation and differentiation of muscle progenitors. Activation of Wnt signalling *via* β-catenin increases MyoD and Myf5 expression, thereby furthering stem cell commitment to the muscle lineage (Lian et al., 2012). Bone morphogenetic proteins (BMPs) also influence muscle differentiation. BMP-2 promotes muscle growth, whereas BMP-4 inhibits myogenesis by preventing stem cell differentiation (Görlitz et al., 2024).

Moreover, mechanical and electric stimulation of skeletal muscles also play an important role in muscular differentiation (Xiang et al., 2025). In vivo, muscles experience mechanical forces from movement and electrical impulses from nerves, both of which are necessary for proper tissue development (Lin et al., 2025). Research indicates that mechanical stimuli, such as regular stretching or dynamic compression, aid muscle fibre alignment, myotube formation, and overall tissue integrity (Rios et al., 2023). Additionally, neurostimuli have been shown to imitate neuromuscular signals and enhance muscle contraction protein expression, resulting in an increased number of functional muscle fibres with a properly organised structure (Cheuy et al., 2023).

The muscle tissue development process is also dependent on biochemical stimuli, notably insulin-like growth factor 1 (IGF-1) and FGF-2 (Deng et al., 2025; Yavas et al., 2025). IGF-1 is known to stimulate muscle cell proliferation and differentiation by activating the PI3K/Akt signalling pathway, which, in turn, increases MyoD expression. Similarly, FGF-2 supports the maintenance of a higher number of satellite cells and their subsequent transformation to mature muscle cells when appropriate conditions are met (Yeh et al., 2023).

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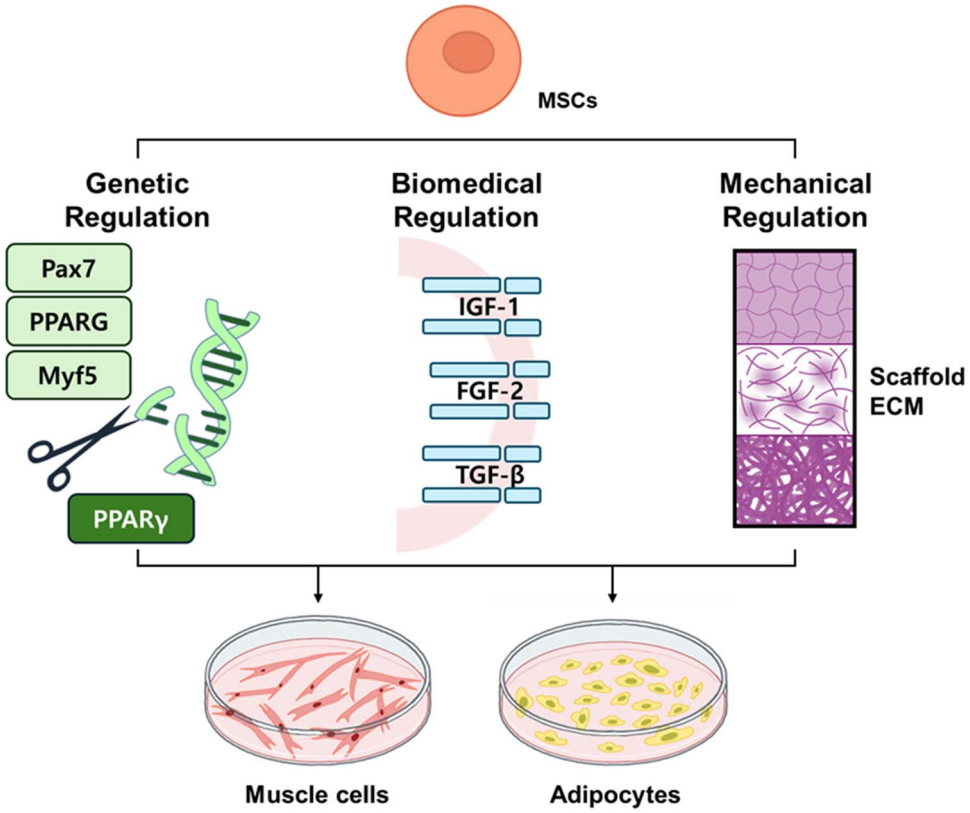


Figure 3. Cell differentiation and co-culture of muscle and fat cells, regulatory mechanisms governing the differentiation of pluripotent or mesenchymal stem cells into muscle and adipose lineages. The diagram summarises three principal modes of control: (1) genetic regulation, mediated by transcription factors such as *Pax7*, *Myf5*, and *PPARγ* that specify myogenic and adipogenic commitment; (2) biomedical regulation, involving growth factors including IGF-1, FGF-2, and TGF-β that modulate proliferation and lineage specification; and (3) mechanical regulation, provided by scaffold architecture and extracellular matrix (ECM) stiffness that influence cellular alignment and maturation. Together, these regulatory cues drive the formation of muscle cells and adipocytes, which constitute the primary cellular components of cultivated meat.

Challenges in myogenic differentiation

One of the most prominent challenges in muscle tissue engineering to produce cultured meat is the fusion and alignment of myotubes. In original muscle tissues, muscle fibres are composed of various structures that contribute to their complexity and functionality (Kadim et al., 2015). To accomplish this, scaffold design is pivotal. Aligned nanofibres or micropatterned surfaces that display a smooth surface for cell adhesion and hydrogel patterns of fibrous scaffolds that allow control of cell growth and orientation hold much potential for muscle tissue engineering (Calero-Castro et al., 2024).

Another significant challenge is ensuring adequate vascularisation and nutrient diffusion in thicker muscle tissues (Pretorius et al., 2021). In living organisms, muscles possess a high vascular density that facilitates the delivery of oxygen and nutrients; however, in vitro conditions often lack sufficient capillary networks, making it difficult for large-volume tissue constructs to survive (Rademakers et al., 2019). This issue has been addressed by coculturing muscle cells with endothelial cell precursors or employing perfusion bioreactors to enhance nutrient transport and improve tissue survival rates (Verbruggen et al., 2018).

Adipogenic differentiation: mechanisms and importance in cultured meat

Adipose tissue plays a crucial role in defining the sensory and nutritional characteristics of meat, including its flavour, tenderness, and juiciness (Wang et al., 2024). The differentiation of adipocyte stem cells is mediated by key transcription factors, notably PPARγ and C/EBPs, which facilitate lipid storage and the maturation of fat cells (Lau et al., 2023).

PPARγ is a transcription factor that regulates the majority of adipose tissue formation and the differentiation of cells into adipose tissue by activating the genes associated with lipid metabolism, fat synthesis, and triglyceride accumulation (De Siqueira et al., 2024). Furthermore, C/EBPα and C/EBPβ act in concert with PPARγ to convert preadipocytes to mature adipocytes that contain large lipid reserves (Li et al., 2024). The supplementation of culture media with insulin and glucose potentiates adipogenic differentiation, as insulin signalling increases fatty acid uptake and storage (Gamwell et al., 2025).

Other aspects of adipogenesis for in vitro cultured meat include managing fat composition and balancing nutritional value with taste. In traditional meat, the saturated, monounsaturated, and polyunsaturated fats affect both the texture and the health implications of the meat (Leivers et al., 2025). By carefully modulating the culture environment, including the ratio of omega-3 to omega-6 fatty acids, it may be possible to influence the lipid profile of cultured adipose tissue, potentially improving its nutritional quality (Ouellette et al., 2019).

In addition, mechanical and biochemical factors play a significant role in fat differentiation (Discher et al., 2009). Stiff matrices promote osteogenesis rather than adipogenesis, whereas softer matrices favour adipocyte formation (Wang et al., 2025). Therefore, controlling scaffold stiffness and composition effectively is crucial for optimal fat differentiation

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(Engler et al., 2006). Moreover, growth factors, such as BMP-4 and retinoic acid, have been studied for their capabilities to stimulate adipogenesis and increase fat tissue growth in tissues cultured for meat products (Tang et al., 2003).

Coculturing muscle and fat cells for improved meat quality

The interplay between muscle and fat is critical to meat quality, as intramuscular fat (marbling) enhances tenderness and taste (Wood et al., 2008). To replicate this attribute in cultured meat, researchers have explored coculture systems that allow muscle and fat cells to grow in tandem. These methods seek to artificially reproduce the tissue composition to improve the sensory properties of cultured meat (Ma et al., 2024). One such strategy is sequential differentiation, which involves initially introducing muscle cells and then adding in factors that induce fat cell proliferation. This approach ensures appropriate spatial organisation and minimises competition for nutrients and signalling messages between different cell types (Ostrovidov et al., 2014). Another approach utilises three-dimensional (3D) bioprinting to produce tissue-engineered meat products with specified muscle-to-fat ratios. By accurately positioning muscle and fat precursors within a scaffold during embedded bioprinting, the complex geometry of traditional meat cuts can be replicated (Murphy & Atala, 2014). Additionally, the incorporation of biocompatible, biodegradable hydrogels containing growth factors has been explored to facilitate spatiotemporal differentiation, enabling the development of muscles and fats under controlled conditions (Pfaff et al., 2025). Concurrently, metabolic engineering strategies are being developed to enhance lipid metabolism in muscle cells, enabling fat-enriched tissues even without prior adipocyte differentiation (Louis et al., 2023).

Scaffold and structural engineering in cultured meat

Biomaterials for scaffolding

A critical step in the production of cultured meat is the formulation of a scaffold. The scaffold serves as a structural framework that supports cell growth and development while contributing to the texture of the final product (Langer & Tirrell, 2004). A scaffold should be biocompatible, edible, porous, and able to support the differentiation and maturation of muscle and adipose tissues (Nurul Alam et al., 2024). Various natural and synthetic biomaterials have been studied to design effective scaffolds for cultured meat (Harvey Ratner & Iveson, 2012).

Natural biomaterials, including collagen, gelatin, chitosan, and alginate, are commonly used because they are biodegradable, bioactive, and resemble the native extracellular matrix (ECM) (Khatun et al., 2025). Collagen and gelatin, derived from animal sources, are particularly effective in supporting cell attachment and proliferation compared to many other materials (Wu et al., 2023). They are also the primary structural proteins in meat, which makes them ideal scaffolding materials (Shoulders & Raines, 2009). Alginate, sourced from seaweed, is also a promising option due to its biocompatibility, hydrophilicity, and ability to form hydrogels that can encapsulate cells and promote differentiation. In the realm of tissue engineering, alginate scaffolds have been successfully utilised in 3D bioprinting and microencapsulation (Lee & Mooney, 2012). When evaluating scaffolds for applications involving cultured meat, cell viability—a crucial indicator of how well cells survive and proliferate on scaffolds—varies among various biomaterials. Self-healing hydrogel matrices represent a recent advance in scaffold biomaterials. These materials contain dynamic, reversible cross-links that maintain stability under physiological conditions. They also enable spatially ordered co-culture of muscle and adipose cells, improving tissue integrity and structural regeneration during development (Table 2) (Hao et al., 2025).

The use of polylactic acid (PLA) and polycaprolactone (PCL) has provided notable advantages in the field of tissue engineering due to their mechanical stability and manipulability (Farah et al., 2016). However, the food safety standards must be consulted regarding the degradation products and tissue construct compatibility (WHO, 2023). Currently, alloyed PLA, PCL, and polyethylene glycol (PEG) serve as exemplary examples of synthetic polymers emerging from modern technological advancements (S et al., 2023). Because of its adjustable degradation characteristics, polylactic-*co*-glycolic acid (PLGA) is another interesting polymer. Its mechanical versatility and control over porosity have been emphasised in biomedical applications, despite its current limited use in scaffolding for cultured meat (Wan et al., 2023). Dynamic boronic ester cross-links in advanced scaffold materials also enable adjustable mechanical properties, creating flexible conditions for tissue maturation and muscle cell growth (Wang et al., 2025). These materials exhibit high kinetic strength and can be modified on a large scale. However, biodegradability, safety, and suitability for cultured meat production are the major concerns regarding synthetic scaffolds. The combination of natural and synthetic materials in hybrid scaffolds represents a relatively new domain that effectively addresses the challenges of mechanical strength, bioactivity, and biostability within a single structure.

Advanced scaffold fabrication techniques

To mimic the texture and consistency of traditional meat, advanced scaffold fabrication techniques have been developed (Murphy & Atala, 2014). These techniques enable precise control over the architecture and mechanical properties of scaffolds, as well as the cellular organisation, thereby improving the quality and scalability of cultured meat production (Hutmacher, 2000). Among these techniques, 3D bioprinting stands out as particularly promising for the fabrication of scaffolds in cultured meat. It allows for the layer-by-layer deposition of cells and biomaterials, facilitating the creation of complex tissue structures that closely resemble meat (Derakhshanfar et al., 2018). Inkjet-based bioprinting is capable of printing bioink-loaded cells on scaffolds, promoting tissue formation from hydrogels (Zhou et al., 2019). Extrusion-based bioprinting utilises hydrogels, collagen, or decellularised ECM (dECM) materials to create fibrous muscle tissues (Li et al., 2022). Additionally, laser-assisted bioprinting allows for high-resolution placement of cells, improving the uniformity of the constructed tissue (Guillotin et al., 2010).

In recent years, ultrafine fibres that promote cell adhesion, splitting, and differentiation have gained considerable attention (Wang et al., 2023). Biomechanical scaffolding, combined with biophysics, enhances the functionality and effectiveness of materials used in tissue engineering. Recent efforts have focused on embedding bioactive molecules and growth factors into culture systems to enhance myogenesis and tissue development. These approaches have driven the widespread adoption of electrospinning technology, one of the most recognised scaffold fabrication methods in tissue engineering (Li et al., 2024), which remains its most recognised application. Rather than focusing on tissue integration, the matrix structure directs attention to the skeletal framework of tissue (Lee et al., 2025). This approach ensures that muscle tissue is integrated with the skeletal structure, thereby

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Table 2. Comparison of scaffold materials and their properties for cultured meat engineering, comparison of scaffold materials and their properties for cultured meat engineering. Each scaffold category—synthetic polymers (e.g., PEG, PLA, PCL, and PLGA), polysaccharides (e.g., alginate), and protein-based biomaterials (e.g., gelatin and collagen)—is evaluated for key attributes relevant to tissue formation, including cell viability, mechanical performance, fabrication method, and edibility. Mechanical properties denote tunable stiffness or structural stability; fabrication methods refer to common techniques such as three-dimensional (3D) printing, electrospinning, and solvent casting. ECM, extracellular matrix.

Category	Material	Cell viability (%)	Mechanical properties	Fabrication method	Edibility	Reference
Synthetic	PEG (polyethylene glycol)	79.50 ± 0.56	Tunable stiffness	Modular hydrogel, Sponge formation	O	(Messineo et al., 2019)
	PLA (polylactic acid)	95.3 ± 2.1	Mechanical stability, manipulability	3D printing	Δ	(Wurm et al., 2017)
	PCL (Polycaprolactone)	~79.6	Mechanical stability, manipulability	Electrospinning, 3D printing	Δ	(Paterson et al., 2024)
	PLGA [poly(lactic-*co*-glycolic acid)]	81.57 ± 1.80	Tunable degradation	Solvent casting, Emulsion	Δ	(Cely-Garcia et al., 2025)
Polysaccharide	Alginate	96 ± 3	Hydrophilic, hydrogel-forming	3D bioprinting, Microencapsulation	O	(Kostenko et al., 2022)
Protein	Gelatin	92.0 ± 3.2	Biodegradable, bioactive, ECM-like	Electrospinning, Self-assembly	O	(Asim et al., 2024)
	Collagen	99.7 ± 2.1	Biodegradable, bioactive, ECM-like, meat structural protein	Electrospinning, Self-assembly, 3D bioprinting	O	(Bayrak et al., 2024)

Note. O = edible; Δ = conditionally edible.

significantly improving its mechanical properties (Wang et al., 2020). As a result, the dexterity and elasticity of the muscle tissue incorporated into the scaffold can be controlled and optimised at various stages.

Another emerging approach involves the use of dECM scaffolds, which are obtained from animal tissues (Josino & Stimamiglio, 2024). These tissues are classified based on their anatomical origin (e.g., muscle, skin, or organ-specific sources), allowing for the preservation of native structural and biochemical cues (Wright, 2017). The resulting natural scaffold retains important nutrients that support the proliferation and differentiation of attached cells (Reginensi et al., 2025). dECM scaffolds have shown positive outcomes in supporting muscle and adipose tissue development for cultured meat production (Wolf et al., 2012). Furthermore, the species origin of the processed material—whether bovine, pig, or fish—is not a significant concern (Gilpin & Yang, 2017). However, the cell source is critical, as the development process of these cells largely determines the steps required before they can be cultivated into a usable, edible form.

Microcarrier-based systems provide an effective method for scaffold filtration, thereby enhancing volumetric yield in bioreactors—vessels used for cell cultivation. These microcarriers are small, spherical particles that facilitate efficient cell adhesion and replication due to their large surface area (Bodiou et al., 2025). They can be composed of materials such as gelatin, alginate, and synthetic polymers, permitting flexible culture conditions. Currently, researchers are utilising edible microcarriers to simplify postharvest adjustments of scaffolds, thereby improving the scalability of cultured meat production (Post et al., 2020).

Innovative approaches aimed at targeting cell-driven tissue organisation through autonomous scaffold self-assembly and organoid construction have been explored (Xu et al., 2024). These self-assembling scaffolds facilitate tissue growth by encapsulating cells and guiding them to produce their own ECM, thereby improving the efficacy of tissue engineering and reducing the reliance on traditional scaffolds (Álvarez et al., 2023). Additionally, functional muscle and adipose tissues can be generated using organoids, which involve aggregating stem cells into 3D tissue structures that mimic the characteristics of the original tissue (Dariolli et al., 2025; Sasai, 2013).

Scaffold design is crucial in the engineering of cultured meat, particularly in terms of the structural and physiological characteristics of the tissues (Sawyer et al., 2023). The integration of advanced biomaterials, fabrication techniques, and bioreactor systems is helping to address key biomechanical challenges, including texture replication, cellular organisation, and large-scale production (Albrecht et al., 2024). To realise the large-scale commercial production and market acceptance of cultured meat products, future work should be done on optimising the scaffold parameters, elevating bioprinting resolution, and strengthening the interactivity between the materials and cells (Schätzlein & Blaeser, 2022).

In summary, scaffolds for cultured meat production can be broadly divided into two main categories: natural and synthetic materials. Natural scaffolds, such as collagen, gelatin, and alginate, provide high biocompatibility and bioactivity, supporting cell adhesion and differentiation. In contrast, synthetic scaffolds, such as PLA-, PCL-, and PEG-based polymers, offer superior mechanical strength, tunable degradation, and structural precision. Hybrid scaffolds that combine both materials are emerging as an optimal approach, balancing biofunctionality with stability. These integrated strategies are expected to play a key role in achieving the desired texture, composition, and scalability of cultured meat.

Bioreactor systems and scaling strategies for cultured meat production

Bioreactor design and functionality

Bioreactors regulate critical parameters, including oxygen and nutrient supply, temperature, agitation, aeration, and pH. Maintaining these factors within optimal ranges is essential for consistent cell and tissue growth (Neuss et al., 2025). Various kinds of bioreactors have been researched for meat cultivation, each

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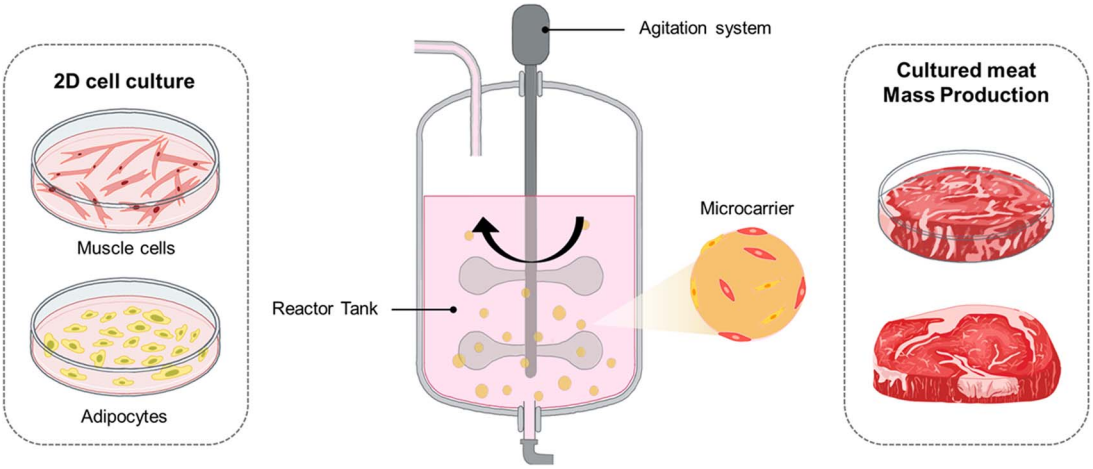


Figure 4. Bioreactor design and large-scale cultured meat production, schematic representation of large-scale cell expansion for cultured meat production using bioreactor systems. The process begins with a two-dimensional (2D) culture of muscle and adipose cells, which serve as seed cultures for scaling. These cells are subsequently transferred into a stirred-tank bioreactor, where an agitation system maintains homogeneous suspension and nutrient distribution. Within the reactor, cells proliferate as aggregates or on microcarriers that provide surface attachment for adherent growth. Continuous mixing enhances mass transfer and prevents cell sedimentation. The expanded cells are then harvested and assembled into cultivated meat tissues, which are further processed into final meat products, illustrating the transition from small-scale cell culture to industrial-scale production.

presenting distinct advantages and disadvantages based on the bioreactor's specific tissue requirements (Bodiou et al., 2025).

Stirred-tank bioreactors are one of the most commonly used systems for large-scale cell cultivation due to their ability to achieve competent mixing and oxygenation (Vikrant et al., 2018). These bioreactors are equipped with impellers that create a well-mixed environment, preventing cell aggregation and ensuring adequate nutrient delivery. This design makes them particularly suitable for suspension cultures of proliferative cells, such as iPSCs or MSCs (Cuesta-Gomez et al., 2023). However, the energy generated from the mixing system can damage adherent cells or delicate tissue constructs, necessitating the implementation of shear-protective methods like encapsulation or the use of microcarriers (Gwon et al., 2024).

Fixed-bed bioreactors use microcarriers or porous scaffolds to facilitate attachment of anchorage-dependent cells, including MSCs and satellite cells. These systems are advantageous for attaining high cell concentrations and ensuring efficient nutrient perfusion during the differentiation and maturation phases of tissue formation. Nonetheless, variations in nutrient availability and waste removal present challenges that require the adoption of dynamic perfusion strategies (Goral et al., 2024).

Perfusion bioreactors actively remove metabolic waste while supplying fresh media to the cultures, thus maintaining the tissue constructs in an optimal environment (Kreye et al., 2019). This approach is especially advantageous for tissue-engineered constructs, as it improves systolic blood flow and enhances cell viability and differentiation. Furthermore, these bioreactors can also be equipped with sensors and automation tools for monitoring and adapting culture conditions in real time (Chen et al., 2025).

Rotating wall vessel (RWV) bioreactors are designed to create and maintain low-shear microgravity conditions, which are conducive to the development of 3D tissue aggregates (Bergstrom et al., 2024). These bioreactors are particularly well suited for growing primary tissue structures as they stimulate cell-to-cell contact while minimising mechanical force. Rotating wall vessel systems have been successfully employed in the cultivation of muscle tissue and the alignment of myofibers in muscle without the need for scaffolds (Nakazato et al., 2022).

Strategies for large-scale cell expansion

To facilitate the industrial production of cultured meats, biocompanies must develop accurate expansion strategies that maximise cell numbers while retaining cell differentiation potential. One possible approach is the use of suspension cultures, in which cells are grown as aggregates or attached to microcarriers in a dynamically stirred environment (Vallabhaneni et al., 2023). These cultures are beneficial to the scaling-up process because they eliminate the limitation of surface area that exists in traditional adherent cell cultures. Cells can, therefore, be grown in larger quantities within bioreactors (Figure 4) (Hauser et al., 2024).

Microcarrier-based cultures facilitate the economical capture of biotic cells by enhancing the surface available for cell adhesion in stirred or perfused bioreactors. Different types of microcarriers, such as hydrogels, biodegradable polymers, and ECM-mimicking coatings, have been manufactured to increase cell adhesion as well as cell differentiation (Allan et al., 2019). Intermittent agitation of the bioreactor, or perfusion flow, is an example of dynamic seeding that can better control the arrangement of microcarriers and cells to reduce random growth (Jeske et al., 2021).

Cell encapsulation methods offer great potential for large-scale cell replication. In this technology, cells are incorporated within hydrogel microspheres or scaffolds, modular spheroids (Kim et al., 2022). The microenvironment must be engineered to balance nutrient exchange with protection from shear stress. Such conditions are particularly important for delicate cell types, including somatic stem cells and myocytes. Furthermore, encapsulation facilitates coculture techniques in which adipocytes and myocytes are cultured in the same bioreactor system. This approach has been shown to enhance the integration of engineered tissues (Nguyen et al., 2019), which may, in turn, influence the structural and sensory properties of cultured meat.

Cost-reduction strategies for industrial scale-up

Current research focuses heavily on making cultured meat production economically viable. One of the greatest challenges lies in the high cost of cell culture, media, and bioreactor operation (Chriki & Hocquette, 2020). Formulations of

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serum-free media are being developed to replace animal-based fetal bovine serum with plant-based or recombinant alternatives, which would greatly reduce the cost of cultured meat (van der Weele et al., 2019). Additionally, the use of inexpensive additives, such as hydrolysates and conditioned media, enables the short-term preservation of cell viability and differentiation potential while optimising growth factor levels (Fan et al., 2024). Other more cost-effective approaches include closing the loop on waste with shredded culture media filtration systems that continually refresh and filter the media (Specht et al., 2018).

Automation and optimisation of the bioprocessing system are essential for effectively duplicating and improving systems to enhance scalability, thereby addressing the need for accuracy (Bomkamp et al., 2022). Accompanying an automated bioreactor system with real-time adjustable monitoring and control sensors streamlines the process, as the culture environment can be changed without manual intervention. To mitigate batch-to-batch variability, there is a need to capture the optimum bioprocess control parameters with predictive modelling and artificial intelligence (AI)–driven process control (Dan et al., 2025).

Techniques focused on reducing waste and promoting circular biomanufacturing are currently under study to improve cost-effectiveness and sustainability. Closed-loop systems that reduce resource use and ecological damage by extracting meat from spent media and cellular waste from the cultured meat process are being developed (Hubalek et al., 2022). As bioreactor technologies mature, these strategies for scaling up will become pertinent for the end commercial viability and sustainability of cultured meat. The continued collaborative and integrative research efforts of biotechnological industry practitioners and experts in food science and bioengineering are likely to result in novel bioprocessing methodologies aimed at high-volume production of quality cultured meat products.

In summary, bioreactors used for cultured meat can be categorised into four major types: stirred-tank, fixed-bed, perfusion, and RWV systems. Each offers distinct advantages depending on the growth and differentiation stage: Stirred-tank reactors enable large-scale proliferation; fixed-bed and perfusion systems support differentiation and tissue maturation; and RWV systems simulate low-shear conditions that enhance 3D tissue formation. Optimising the combination of these bioreactor systems will be essential for achieving efficient, scalable, and cost-effective cultured meat production.

Public perception and market readiness of cultured meat

Beyond technical progress, the commercialisation of cultured meat depends heavily on three factors: consumer perception, social acceptance, and effective marketing strategies (Table 3) (Pakseresht et al., 2022). The public's perception of cultured meat is still mixed, despite growing interest in ethical and sustainable food alternatives. This is due to several factors, including perceived naturalness, food neophobia, trust in science, and ethical considerations. According to studies, people around the world are wary of cultured meat because they do not know how it is made and think it's "artificial" or "unnatural" (Pakseresht et al., 2022). Transparent communication regarding the technology, its potential advantages, and safety is necessary to allay these concerns (Lewisch & Riefler, 2023). Labelling tactics are also important; for instance, "cultivated meat" or "cell-based meat" are typically preferred over "lab-grown" or "synthetic" because of their more favourable connotations (Liu et al., 2023).

Customers are more likely to try and eventually embrace cultured meat products when marketing strategies prioritise food security, environmental sustainability, and animal welfare (Tsvakirai, 2024). Nonetheless, there are notable differences in acceptance between demographics, with younger, eco-aware consumers typically being more receptive to adoption than older or more conservative groups. The rate of market readiness will be influenced by consumer attitudes, pricing strategies, and the clarity of regulations (Monaco, 2025). Frameworks for approval, labelling, and safety assessment are presently being developed by regulatory bodies in the United States, Singapore, and the European Union (Floor & Manlosa-Kirk, 2025).

Although maintaining price parity with traditional meat is still very difficult, continuous cost-cutting in cell culture media and bioprocessing could eventually increase economic viability (Hallman et al., 2023). Overall, consumer education, trust-building, and accessible product positioning are key to ensuring cultured meat can transition from a scientific innovation to a widely accepted food option.

Conclusion and future directions

Cultured meat advancements represent a revolution in food production, offering the potential for sustainable, ethical, and large-scale production, a stark contrast to traditional animal farming (Post et al., 2020). Researchers and industry stakeholders are diligently working to develop meat products that replicate the taste, texture, and nutritional profile of conventional meat through innovations in stem cell biology, agricultural bioprocessing, tissue engineering, and optimisation. While significant progress has been made, numerous scientific and technological hurdles remain before cultured meat can achieve global consumption (Soleymani et al., 2024).

A primary focus for future research is enhancing the efficiency of muscle and fat cell differentiation (Bhat et al., 2019). Controlling stem cell fate and directing tissue-specific differentiation is crucial for producing high-quality cultured meat. Furthermore, novel biomaterials and microenvironments that mimic the native ECM can significantly enhance differentiation by providing appropriate biochemical and physical cues (Mishra et al., 2025).

Innovations in scaffolds and biomaterials are essential for engineering the texture and sensory attributes of cultured meat (Park et al., 2025). While alginate has been widely used due to its natural polymer properties, there is a shift towards other polymers that offer desired stiffness, tunable parameters, and functionality (Lee & Mooney, 2012). Self-assembling biomaterials, nanofiber-based scaffolds, and decellularised plant scaffolds are being developed to enhance meat mimicry. Self-healing scaffolding technologies based on reversible and physiologically stable cross-links improve tissue architecture and maintain marbling integrity in cultured meat. These systems can better replicate the complex structural characteristics of conventionally produced meat (Hao et al., 2025). Incorporating vascularisation through perfusable scaffold networks, oxygen-releasing biomaterials, or other perfusion strategies can improve cell survival and tissue maturation in thicker cultured meat scaffolds.

Beyond cells and biomaterials, developing an efficient and economical manufacturing process is a major challenge for commercialisation. A critical issue is the high cost of cell culture media, including growth factors and recombinant proteins (van der Weele et al., 2019). Implementing bioreactors at a large scale will offset these costs, driving the cultured meat industry forward (Post et al., 2020). Current bioreactors only meet small-scale

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Table 3. Consumer perceptions, regulatory, and market factors affecting cultured meat commercialisation, consumer perceptions, regulatory, and market factors affecting cultured meat commercialisation. The table categorises major determinants of market readiness into six domains: consumer perception, terminology/labelling, marketing strategy, demographic trends, regulatory and policy environment, and economic feasibility. Each row lists positive influences that facilitate acceptance—such as ethical appeal, sustainability awareness, or supportive regulation—and barriers or concerns that hinder adoption, including perceptions of unnaturalness, labelling confusion, policy uncertainty, and price gaps relative to conventional meat.

Category	Positive influence	Barrier/concern
Consumer Perception	Ethical appeal, Sustainability, Curiosity	Artificial image, Food neophobia, Unnaturalness perception
Terminology/ Labeling	"Cultivated" or "cell-based" terms are more accepted	"Lab-grown" or "Synthetic" evoke distrust/disgust
Marketing Strategy	Focus on animal welfare, food security, and the environment	Misaligned messaging, Lack of consumer education
Demographics	Younger, eco-conscious, educated consumers	Older, conservative, rural populations
Regulation & Policy	Clear frameworks in Singapore, the United States, and the European Union are emerging	Lack of harmonisation, Uncertainty
Economic Feasibility	Cost-cutting in media, Scaling potential	Price gap *versus* conventional meat remains large

needs. Achieving productivity gains requires ongoing engineering innovations in bioprocessing; Otherwise, quality and productivity may decline (Müller et al., 2022). Artificial intelligence and machine learning can enhance bioreactor efficiency by enabling real-time monitoring and automated adjustments. In parallel, modular and decentralised production systems reduce logistical barriers by supporting local cultured meat manufacturing. This approach minimises transportation emissions and improves overall supply chain efficiency (Moss, 2025). Finally, establishing safety and labeling standards for cultured meat products is crucial for regulation and consumer acceptance (Lee & Mooney, 2012). International efforts are underway to streamline procedures that foster consumer trust and ensure the integrity of the production process.

In addition to ongoing efforts to improve scalability and reduce production costs, several emerging technologies are expected to accelerate the next phase of cultured meat development. Synthetic biology offers powerful tools for engineering cell lines with enhanced growth efficiency and for designing cost-effective media formulations through controlled expression of growth factors and metabolic pathways (Stout et al., 2024). Artificial intelligence–guided media optimisation integrates high-throughput screening with machine learning algorithms to identify optimal combinations of nutrients and signalling molecules, thereby improving reproducibility and reducing batch-to-batch variability (Nikkhah et al., 2023). Furthermore, 3D bioprinting technologies enable precise spatial organisation of muscle, fat, and connective tissues, supporting large-scale fabrication of structured meat products with consistent texture and composition (Kang et al., 2021). Together, these approaches represent promising frontiers that bridge fundamental cell biology with scalable, reproducible, and economically viable production systems. In addition to advances in cultured meat based on animal cells, emerging research is exploring the potential of plant cell–based systems and hybrid approaches that integrate both animal and plant components. Plant cell cultures offer advantages such as lower production costs, simpler culture conditions, and reduced regulatory hurdles. Moreover, the structural properties of plant tissues—such as cellulose-rich scaffolds—can be leveraged to provide desirable texture and improve scalability. Hybrid cultured meat, which combines animal cells with plant-derived materials or plant-based proteins, represents a promising strategy to enhance sensory quality while lowering production costs. This integrative approach could broaden product diversity, improve nutritional profiles, and accelerate market adoption by bridging the gap between conventional plant-based and cell-based products (Baune et al., 2023; Maharjan et al., 2025; Park et al., 2024).

Data availability

No new data are generated in this manuscript.

Author contributions

Sungmin Kim (Conceptualisation, Writing—original draft, Writing—review & editing [lead]), Yeojeong Jeong (Visualisation, Writing—review & editing [equal]), Hyeju Jo (Visualisation, Writing—review & editing [equal]), Yun-Gwi Park (Visualisation, Writing—review & editing [equal]), Sung-Hwan Moon (Funding acquisition, Supervision [lead], Writing—review & editing [equal])

Conflicts of interest

None declared.

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