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Feeding the future: The evolution, sustainability and acceptability of artificial meat

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Abstract

The global food system is currently confronting a "protein paradox," where the rising demand for animal-sourced proteins intersects with the ecological exhaustion of traditional livestock farming. As of 2026, conventional meat production accounts for approximately 14.5% to 18% of global greenhouse gas emissions and utilizes nearly one-third of the world's fresh water, rendering the current model unsustainable for a projected population of 9 billion by 2050. This review examines the evolution of artificial meat—an umbrella term encompassing plant-based analogues, fermented proteins, and cell-based (cultured) meat—as a critical solution to this crisis. Technological advancements have facilitated a transition from laboratory-scale experiments to industrial pilot plants utilizing 20,000-liter bioreactors, supported by breakthroughs in serum-free growth media and 3D/4D bioprinting. These innovations allow for "nutritional tuning," such as enhancing omega-3 profiles, and eliminate biological hazards like *Salmonella* and zoonotic diseases. However, the industry faces significant hurdles, including the "yuck factor" of consumer neophobia, high production costs, and a fragmented global regulatory landscape marked by nomenclature disputes and stringent "Novel Food" frameworks. While life-cycle analyses suggest cultured meat could reduce land use by 99% and water use by up to 96%, its long-term climate superiority depends on the decarbonization of energy grids. This paper synthesizes current data to evaluate the feasibility of cellular agriculture, concluding that while it offers a transformative path for food security and animal welfare, its success remains contingent upon achieving price parity and fostering public trust.

Keywords: Cellular agriculture, cultured meat, 3D bioprinting, food security, protein paradox, sustainability

Introduction

The global food system is currently navigating a period of unprecedented volatility and structural transformation. At the heart of this shift is the "protein paradox" while animal-sourced proteins remain a foundational component of human nutrition and cultural identity, the conventional methods of producing them are increasingly incompatible with the biophysical limits of the planet. As we move through 2026, the livestock industry finds itself at a critical position. Projections from the Food and Agriculture Organization (FAO) and independent researchers suggest that to maintain current per capita meat consumption for a global population peaking at 9 billion by 2050, meat production must increase by a staggering 50% to 73% (Post *et al.*, 2020; FAO, 2026) [28]. However, the traditional agricultural model—reliant on land-intensive grazing and grain-heavy feedlots—is reaching its ecological ceiling. Historically, the livestock sector has been a primary driver of environmental degradation. It accounts for approximately 14.5% to 18% of anthropogenic greenhouse gas (GHG) emissions (Lee *et al.*, 2025; Twine, 2021) [20, 34].

The sector significantly contributes to biodiversity loss through land conversion, as agriculture is the dominant cause of species extinctions due to the transformation of complex natural ecosystems into simplified human-dominated systems (Cravino *et al.*, 2024) [8]. Furthermore, animal production is a massive consumer of resources, utilizing nearly one-third of the world's fresh water—a total water footprint significantly larger than that of crop products with equivalent nutritional value (Mekonnen & Hoekstra, 2012) [25].

Beyond environmental impacts, the emergence of zoonotic diseases such as avian influenza and the rise of antimicrobial resistance (AMR) linked to intensive farming have reframed

meat production as a critical public health concern (Hafez & Attia, 2020) ^[16]. The abuse of antibiotics as growth promoters in industrial livestock systems is a primary driver of resistant bacteria, posing a direct threat to human health (Hafez & Attia, 2020) ^[16]. In response to these "wicked problems," a new frontier of food science has emerged: the development of artificial meat alternatives.

The term "artificial meat" serves as an umbrella for a diverse array of technologies that decouple protein production from traditional animal husbandry. These range from established plant-based analogues to the more recent commercialization of "cultured" or "cell-based" meat. In the early 2020s, plant-based products led the charge, leveraging sophisticated extrusion techniques to mimic the fibrous texture of muscle. By 2026, however, the narrative has shifted toward cellular agriculture—the process of growing real animal tissues in bioreactors using stem cell technology. This evolution represents a fundamental shift from a "farming" mindset to a "manufacturing" mindset, where food is engineered at the molecular and cellular levels to optimize for health, ethics, and sustainability.

Technologically, this period has been marked by a transition from laboratory-scale proof-of-concept to industrial-scale pilot plants. The first lab-grown burger, unveiled in 2013, cost over \$300,000 today, specialized bioreactors exceeding 20,000 liters in capacity are bringing costs down toward price parity with premium conventional cuts (Mridul, 2025) ^[26]. This progress is supported by breakthroughs in serum-free growth media, which eliminate the ethical and economic burden of using fetal bovine serum, and the integration of 3D bioprinting to create complex tissue structures such as steaks and fillets (Yang *et al.*, 2024) ^[35].

Socio-economically, the rise of artificial meat has sparked a global debate over food sovereignty, rural livelihoods, and the definition of "meat" itself. While early adopters in urban hubs view these products as a "clean" and "guilt-free" alternative, traditional agricultural stakeholders have lobbied for strict labelling laws, arguing that the term meat should be reserved for animals raised and slaughtered in the traditional manner (Food Compliance International, 2026) ^[12]. Meanwhile, regulatory landscapes are diverging; while

Singapore and the United States have established robust frameworks for cell-based approvals, other regions remain cautious, balancing innovation against the "yuck factor" and cultural resistance.

Ultimately, the evolution of artificial meat is not merely a story of technological triumph but a reflection of a changing human relationship with the natural world. This review synthesizes the most recent data to evaluate whether these alternatives can truly fulfill their promise of feeding the future without costing the earth.

Production Methodologies

1. Plant-Based and Fermented Analogues

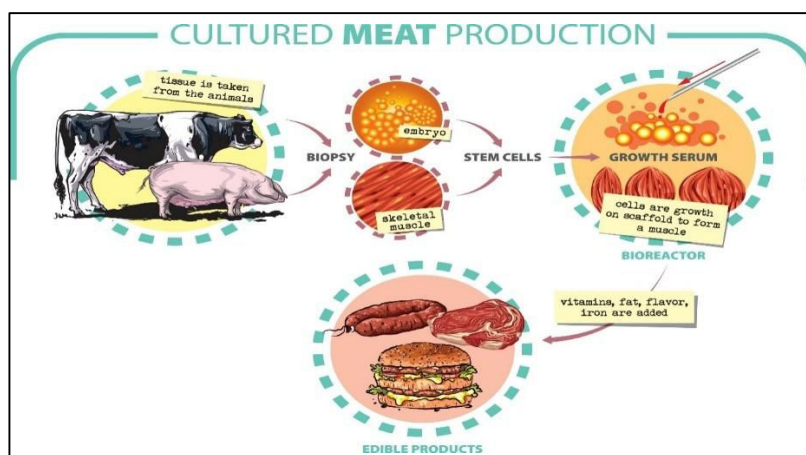
The structural mimicry of meat is primarily achieved through Thermo-Extrusion, where vegetable proteins are heated and sheared to create fibrous fibrils (MDPI, 2023) ^[24]. Recent advances include fermentation, where microbial consortia (e.g., *Bacillus subtilis*) enhance nutrient digestibility and reduce allergens in plant-based matrices (Bohrer, B. M. (2023) ^[3].

2. Cultured Meat Techniques

Cultivated meat relies on three core technologies to move from 2D cell monolayers to 3D tissues:

Scaffolding Techniques

Scaffolding provides the essential 3D structural and biochemical support for cell adhesion, proliferation, and differentiation into mature muscle fibres. In this approach, satellite cells or myoblasts are seeded onto edible, biodegradable meshes—often composed of animal-derived proteins like collagen or gelatin, or plant-based materials like soy and cellulose (Bomkamp *et al.*, 2021) ^[4]. Scaffolds can be engineered with parallel microchannels or anisotropic patterns to mimic the natural extracellular matrix (ECM), encouraging myoblasts to align and fuse into functional multinucleated myotubes (Li *et al.*, 2022) ^[21]. Recent research has explored hybrid scaffolds, such as gelatin-soymilk composites, which combine the bioactivity of animal proteins with the mechanical stability and cost-effectiveness of plant materials (Li *et al.*, 2022) ^[21].



3. 3D/4D Bio-printing

This technique utilizes "bio-inks"—a combination of living cells and supportive hydrogels—to build tissues layer-by-layer according to precise Computer-Aided Designs (CAD) (Yang *et al.*, 2024) ^[35]. By layering muscle, fat, and connective tissue cells simultaneously, 3D bioprinting can create structured products like steaks that traditional

scaffolding cannot easily achieve (Kumar *et al.*, 2021) ^[18]. 4D bioprinting introduces "smart materials" that allow the printed structure to undergo physical or chemical changes (such as shape-shifting or texture modification) in response to external stimuli like temperature or pH changes (Ghazal *et al.*, 2022) ^[13].

4. Self-Organizing Techniques

Unlike scaffolding which uses isolated stem cells, self-organizing methods involve the *in vitro* cultivation of existing muscle tissue explants (Benny *et al.*, 2022) [2]. This method relies on the collective communication of constituent cells-using cell-cell signaling and tissue mechanics-to maintain the complex, organized spatial patterns of functionally distinct cell fates (PMC-2024) [27]. It harnesses the inherent ability of explanted tissue to proliferate while retaining its original composition of muscle, fat, and circulatory cells, resulting in a product that most closely resembles the biological complexity of native meat (Benny *et al.*, 2022) [2].

Sustainability and Environmental Impact

Life-cycle analyses (LCA) indicate that cultured meat could reduce land use by up to 99% and water use by 82-96% compared to conventional beef production. Conventional livestock systems, particularly beef, are major drivers of land degradation and biodiversity loss due to the extensive space required for grazing and feed crop cultivation. By decoupling meat production from live animal rearing, cellular agriculture bypasses the inherent biological inefficiencies of converting plant calories into animal muscle (Tuomisto *et al.*, 2011) [33].

The climate impact of cultured meat differs qualitatively from traditional ranching-Conventional livestock contribute approximately 14.5% to 18% of global greenhouse gas (GHG) emissions, characterized largely by methane from enteric fermentation in ruminants (Lynch & Pierrehumbert, 2019) [23]. Cultured meat emissions are almost entirely carbon dioxide generated from the fossil energy required to power bioreactors and maintain precise temperature controls for cell growth. While methane is a more potent GHG, it does not accumulate in the atmosphere as long as methane. Therefore, the long-term climatic superiority of cultured meat is contingent upon the availability of a decarbonized energy grid (Tuomisto *et al.*, 2011) [33].

Modified livestock systems offer specialized solutions for reducing agricultural runoff. A prominent innovation is the "Enviro-pig," which was engineered with a phytase gene in its salivary glands to enhance the digestion of plant phosphorus (Childers *et al.*, 2011) [7]. In conventional swine, a significant portion of dietary phosphorus is excreted because pigs lack the enzymes to break down phytate found in cereal grains (Shurson & Kerr, 2023) [30]. By allowing the pig to utilize more phosphorus, the phosphorus content in manure is reduced by up to 60%, directly addressing the issue of water eutrophication-where excess nutrient runoff causes algal blooms and "dead zones" in aquatic ecosystems (Childers *et al.*, 2011) [7].

Health, Safety, and "Nutritional Tuning"

The transition to cellular agriculture marks a significant shift in food safety and nutritional design, moving from a system of reactive management to one of proactive engineering.

A primary advantage of cellular agriculture is the elimination of biological hazards inherent to animal slaughter. Conventional industrial farming often suffers from faecal contamination; research indicates that nearly 100% of sampled ground beef may contain bacteria signifying faecal contamination. By decoupling meat production from the digestive and excretory systems of living animals, cultured meat avoids this risk entirely.

Sterile bioreactors operate in closed environments, virtually eliminating common foodborne pathogens such as *Salmonella*, *E. coli*, and *Listeria* (Yuen *et al.*, 2022) [36]. Furthermore, this system mitigates the risk of zoonotic spillovers, such as avian influenza, which thrive in high-density livestock environments.

Cellular agriculture allows for "profiled meat," where the nutritional content is designed at the cellular level. Scientists can adjust lipid profiles by supplementing the cell culture medium with plant or algal-based oils, effectively replacing saturated fats with omega-3 polyunsaturated fatty acids (Amin *et al.*, 2021) [1]. This "tuning" can transform meat from a source of dietary cholesterol into a functional food with anti-inflammatory properties.

Despite these benefits, the industry faces critical hurdles. While bioreactors are sterile, the risk of contamination during industrial scaling remains. If antibiotics are used as a preventative measure, it could exacerbate the global threat of antimicrobial resistance (AMR) (Sogore *et al.*, 2024) [32]. Additionally, the rapid proliferation required for mass production may lead to unexpected epigenetic modifications in cell lines, necessitating rigorous long-term safety monitoring.

Market Acceptability and Regulatory Challenges

The commercial viability of artificial meat is dictated as much by psychological perception as by technological capability. As these products move from the laboratory to the supermarket, they face a complex landscape of consumer skepticism and protectionist regulatory hurdles.

Market adoption is fundamentally linked to the "Meat Paradox"-the psychological conflict where individuals enjoy eating meat but experience moral discomfort regarding animal slaughter and environmental degradation (Loughnan *et al.*, 2010) [22]. Global surveys indicate that younger, urban, and more educated individuals show the highest willingness to adopt cultured meat, often viewing it as a solution to ethical and environmental crises. Studies consistently show that males are more open to trying cultured meat than females, although females often show a higher appreciation for the animal welfare benefits (Bryant & Barnett, 2020) [6]. A primary barrier to acceptance is the perception of "unnaturalness." Many consumers experience a visceral reaction of disgust, termed the "yuck factor," when contemplating meat grown in a bioreactor rather than on a farm. This perceived artificiality leads to "neophobia"-the fear of new foods-and concerns over long-term health consequences that are not yet fully understood by the general public (Siegrist & Sütterlin, 2017) [31].

Animal Welfare in Global Food Systems

Public concern regarding the ethical treatment of livestock is rising, particularly in developed nations, where many now question the moral validity of using animals in food production (Latvala *et al.*, 2012) [19]. Consequently, synthetic and alternative meats are gaining traction as they provide a comparable eating experience without the associated welfare stigmas (Richardson *et al.*, 1994) [29]. Plant-derived, fungal, and lab-grown meat technologies offer a path toward drastically reducing the number of animals required for global protein needs (Croney *et al.*, 2012) [9]. However, total replacement remains difficult for two reasons:

- **Serum Dependency:** Cultured meat techniques frequently utilize fetal calf serum, preventing a completely animal-free process (Datar *et al.*, 2010) ^[10].
- **Agricultural Integration:** Ruminants remain essential components for the functionality of integrated farming ecosystems (Hou *et al.*, 2008) ^[17]

Regulatory Landscape

The regulatory pathway for artificial meat is far from unified, creating a fragmented global market that complicates international trade.

- **Licensing and Global Approval:** Singapore remains the global pioneer, having established the first regulatory framework and granted approvals as early as 2020. In the United States, a joint framework between the FDA and USDA governs the production and labelling of cell-cultured meat, focusing on safety from cell harvest to the final product (Gottlieb, 2018) ^[14]. Conversely, the European Union applies strict "Novel Food" regulations, which often act as a de-facto barrier, particularly for products involving genetic modification (GM), which face intense political and public scrutiny (Guthman *et al.*, 2023) ^[15]
- **Nomenclature and The "War of Words":** Traditional livestock industries have launched significant lobbying efforts to protect the term "meat." Legal battles in regions like Canada and various US states have centered on whether plant-based or lab-grown products can use terms like "burger," "sausage," or "steak". These "truth in labeling" laws are often framed as consumer protection measures to avoid confusion, but they are viewed by the artificial meat industry as anti-competitive barriers designed to maintain the status quo of the conventional meat market (Broaders, S., 2022) ^[5].

Conclusion

Artificial meat has transitioned from a niche concept to a critical pillar of food security. The evolution of meat from traditional animal husbandry to laboratory-scale cultivation represents a paradigm shift in global food security, transitioning "artificial" alternatives from a niche concept to a critical necessity for feeding a projected population of 9 billion by 2050. While plant-based substitutes have achieved market maturity through advanced texturization and fermentation techniques, the scalability of cultured meat remains contingent upon significant breakthroughs in reducing the production costs of serum-free growth media and mastering complex tissue engineering methods.

Currently, the industry is transitioning from laboratory proofs-of-concept to industrial pilot plants using bioreactors exceeding 20,000 liters. These systems utilize scaffolding and 3D bioprinting to replicate the fibrous architecture of animal muscle without the environmental externalities of conventional ranching, which accounts for up to 18% of global greenhouse gas emissions. Beyond sustainability, cellular agriculture offers "nutritional tuning," allowing scientists to replace saturated animal fats with heart-healthy omega-3 fatty acids during the cultivation phase.

However, the industry must navigate a fragmented global regulatory landscape-marked by intense nomenclature disputes over the term "meat" and stringent "Novel Food" frameworks-while simultaneously addressing deep-seated consumer skepticism rooted in the "yuck factor" and perceptions of unnaturalness. In regions like the European

Union, strict GMO regulations pose a de-facto barrier to entry, whereas Singapore and the USA have established more progressive joint-agency approval paths. Ultimately, the long-term success of this technological revolution depends on achieving price parity with conventional beef, ensuring rigorous safety through sterile production environments that eliminate common foodborne pathogens like *Salmonella*, and fostering public trust through transparent, science-backed communication regarding the ecological and ethical benefits of cellular agriculture as a permanent fixture of the global diet.

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