Dean&Francis
ISSN 2959-409X

# The Attributes Influence Organic Properties of Cultivated Meat and Some Improving Strategies

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**Abstract:**
Cultivated meat has emerged as a promising sustainable protein source with potential to alleviate food security pressures, reduce environmental burdens, and minimize animal slaughter. Yet, its sensory attributes—appearance, texture, aroma, and flavor—remain critical barriers to consumer acceptance. This paper systematically examines the key factors shaping these properties. The mechanical characteristics of scaffolds, including elasticity, stability, and deformability, directly influence muscle fiber alignment, textural hierarchy, and the accumulation of flavor precursors. Oxygen partial pressure and culture medium composition jointly regulate myoglobin synthesis and color stability. Meanwhile, lipid type and post-processing methods determine the spectrum of volatile compounds generated during heating, particularly through Maillard reactions and lipid oxidation. Current limitations include insufficient aroma complexity, limited textural diversity, and uneven coloration. To address these challenges, integrated strategies are proposed: refining scaffold design and post-processing control, optimizing culture media formulations, and selecting appropriate lipid sources. Together, these approaches provide a technical roadmap for enhancing the sensory quality of cultivated meat, thereby supporting its product development and industrialization.

**Keywords:** Cultivated meat; Organoleptic property; Scaffold; Maillard reactions.

## 1. Introduction

The increasing frequency of extreme weather, the polarization between the rich and poor, leads to an imbalance between demand and supplementation. Finally, it causes the larger and larger food supplement gap. Traditional food production is regarded as an inefficient way to provide energy and nutrients, especially for meat [1]. It is urgently necessary to explore a new and efficient way of grain production. Cultivated meat is an expective solution as a great potential way to ease the supplementary problem under this surrounding situation [2]. Organoleptic properties are fatal attributes influencing the popularization of cultivated meat.

Although nutrition and safety are the essential characteristics of food, compared to enjoyment, these characteristics are usually invisible. Enjoyment which has a close relationship with sensor stimulates is apparent and immediate character of food. Additionally, it is one of the most direct and instinctive driven force forming and regulating dietary behavior. Enjoyment reflects the satisfaction and pleasurable experience that food brings through its sensory attributes such as color, aroma, taste, texture, and appearance. Enjoyment is not only about the pleasure taste, but also involves smell, sight, touch, and even psychological associations and emotional projections [3]. A pleasurable food can evoke memories, stimulate emotions, and even influence social behavior and a sense of well-being. In modern food science and industrial development, pleasure is no longer an added value but has become one of the core indicators in product design, sensory evaluation, and market positioning. The experience of pleasure begins with sensory reception, which includes attributes such as appearance, texture, and aroma.

Although the sensory attributes of cultured meat represent the most immediate and intuitive dimension of consumer evaluation, prior research has consistently relegated them to a relatively secondary position, with limited systematic or in-depth investigation. This oversight has constrained the market acceptance of cultured meat and impeded its integration into broader dietary culture and consumer psychology [4].

The present study seeks to address this gap by conducting a comprehensive review and analysis of the key determinants shaping the sensory properties of cultured meat. Particular attention is devoted to three critical domains: the formation and stabilization of appearance and color, the regulatory mechanisms underlying texture construction, and the fundamental principles governing textural characteristics.

Building upon existing research findings and industrial practices, this study advances targeted and practicable strategies for improvement, with the dual aim of providing a robust theoretical foundation and delineating actionable pathways for enhancing the sensory quality of cultured meat products. Moreover, this research endeavors to construct an integrated framework of "mechanistic analysis—technological refinement" to guide future product development, process optimization, and market deployment. In doing so, it aspires not only to reinforce the nutritional adequacy and safety of cultured meat but also to elevate its capacity to deliver sensory pleasure and consumer value.

# 2. Differences Between Conventional Meat Products and Cultured Meat

## 2.1 Appearance Characteristics

Conventional livestock and poultry meat products typically exhibit a natural fibrous texture formed by the interweaving of muscle fiber bundles and connective tissue. This structure is accompanied by a distinct red or reddish-brown hue imparted by myoglobin, as well as uneven color distribution arising from differences in slaughter sites and muscle types. Fat tissue is often embedded between muscle fibers in a marbled pattern, producing characteristic gloss and depth. By contrast, cultured meat generally achieves a muscle fiber–like structure through plant protein fibrillation or cell-scaffold cultivation, thereby mimicking the texture of natural meat. Its coloration is usually derived from plant pigments (e.g., betanin, anthocyanins) or heme analogs (e.g., soy leghemoglobin), rather than myoglobin, resulting in a more uniform distribution that lacks the natural color variation associated with different anatomical sites in conventional meat [5]. Fat simulation is typically achieved through dispersed plant oils or cultured adipocytes, producing a marbling-like visual effect, though with comparatively simplified layering [6].

## 2.2 Textural Properties

The chewiness of conventional meat primarily originates from the spatial conformation of myofibrillar proteins (actin and myosin) and the arrangement of muscle fibers. Elasticity, toughness, and juiciness are jointly influenced by fiber diameter, connective tissue content, and thermal processing conditions. Moderate intramuscular fat content further enhances flavor release and oral lubrication during heating, thereby improving overall textural pleasure. In cultured meat, chewiness is largely dependent on the fibrillar alignment of plant proteins or the construction of myofibril-like structures during cell cultivation [7]. Elasticity and toughness are often modulated through the incorporation of hydrocolloids, modified starches, or cross-linking agents, resulting in a more uniform mouthfeel. Juiciness relies on oil-encapsulation techniques or water-retention agents, which release lubricating sensations upon heating; however, this mechanism differs from the natural flavor release associated with intramuscular fat in conventional meat [8].

## 2.3 Aroma Characteristics

During heating, conventional meat generates a wide array of volatile compounds through Maillard reactions, lipid

ISSN 2959-409X

oxidation, and amino acid degradation. These include aldehydes, ketones, sulfur-containing compounds, and pyrazines, which collectively form the characteristic aroma profile of cooked meat. Variations in animal species, rearing conditions, and muscle sites lead to differences in the relative proportions of these compounds, thereby producing distinctive flavor fingerprints. In cultured meat, flavor is primarily achieved through the addition of flavor precursors and subsequent Maillard reactions during heating [9]. Plant-based cultured meat often relies on reactions among amino acids, reducing sugars, and plant-derived lipids to generate aldehydes, pyrazines, and related compounds that mimic roasted meat aromas, though sometimes accompanied by subtle beany or cereal-like notes [10]. Cell-cultured meat, being derived from animal cells, exhibits a flavor profile closer to that of conventional meat, yet still requires modulation of lipid composition and supplementation with flavor enhancers to enrich its overall aroma spectrum.

## 3. Factors Influencing Sensory Properties

### 3.1 Scaffolds

A scaffold is a porous three-dimensional structure that serves as a template for tissue formation, typically mimicking the extracellular matrix to facilitate cell adhesion, proliferation, and/or differentiation. By providing both physical and biochemical cues, scaffolds promote cell attachment, growth, and lineage specification, while also generating spatial heterogeneity in the final product to better replicate the structure and texture of natural meat [11].

The mechanical properties of scaffold materials—including elastic modulus, tensile strength, shear strength, and toughness—play a pivotal role in both tissue construction and the ultimate formation of sensory quality in cultured meat.

First, scaffold stiffness directly influences muscle cell adhesion, spreading, and differentiation. Under the guidance of scaffold materials, cultured tissues gradually develop muscle fiber–like structures with relatively uniform and orderly alignment [9]. Compared with conventional meat, however, the overall architecture is simplified, lacking the multilayered spatial networks formed by the interweaving of muscle bundles and connective tissue [9]. While such structural uniformity contributes to consistency in the appearance and morphology of cultured meat, studies have demonstrated that when the scaffold's elastic modulus approximates that of native muscle tissue, deposition of myofibrillar proteins is enhanced and fiber alignment is strengthened [7]. This, in turn, imparts a fibrous texture and layered chewiness more closely resembling that of conventional meat.

Second, the mechanical stability of the scaffold determines whether its three-dimensional integrity and inter-fiber spacing can be maintained throughout the cultivation process—an essential factor in replicating the spatial distribution of natural muscle bundles [12]. If the scaffold is excessively soft, cell alignment may become disordered and fiber orientation insufficient, thereby reducing elasticity and toughness [13]. Conversely, if the scaffold is overly rigid, it may inhibit cell migration and fusion, leading to inadequate tissue density and negatively affecting juiciness and the overall coordination of mouthfeel.

Moreover, the deformability of scaffolds and their capacity for stress transmission influence the mechanosensory perception of cells during cultivation, thereby regulating sarcomere formation and protein synthesis in muscle cells [14]. This process not only shapes textural attributes but also indirectly affects the accumulation of flavor precursors (e.g., free amino acids and lipids), which in turn contribute to the aroma profile upon heating [10,14].

In summary, the mechanical properties of scaffold materials—by modulating cellular behavior, tissue architecture, and the accumulation of flavor precursors—collectively determine the multidimensional sensory performance of cultured meat, including appearance, textural elasticity, and aroma complexity. Scaffold design thus emerges as a critical determinant of final product quality. To achieve meat-like sensory attributes, scaffolds must not only approximate the mechanical properties of native muscle tissue—ensuring realistic fiber alignment and chewiness—but also exhibit high biocompatibility, supporting cell adhesion, growth, and differentiation to form stable and functional tissue structures. Insufficient mechanical strength often results in loose textures lacking resilience, whereas poor biocompatibility may compromise cell viability and tissue maturation, thereby diminishing overall sensory performance.

Accordingly, scaffold design requires a dynamic balance between mechanical performance and biocompatibility. Recent advances in three-dimensional scaffolds offer promising solutions to this challenge. Features such as porous architectures, biomimetic fiber alignment, and tunable mechanical strength enable closer replication of the native muscle microenvironment. Meanwhile, bio-scaffolds fabricated from biodegradable or natural polymers demonstrate significant advantages in enhancing cell compatibility and promoting tissue maturation. The integration of these approaches not only reconciles the trade-off between mechanics and biocompatibility but also establishes a foundation for cultured meat products that more closely approximate the appearance, texture, and flavor of conventional meat.

## 3.2 Oxygen Partial Pressure and Nutrient Composition of the Culture Medium

### 3.2.1 Color

During the in vitro cultivation of cultured meat, the formation and stability of color are primarily determined by the content and chemical state of myoglobin and its derivatives. Among the key regulatory factors, oxygen partial pressure and nutrient composition of the culture medium play decisive roles. An appropriate oxygen partial pressure promotes aerobic metabolism and myoglobin synthesis in muscle cells. When the oxygen level in the culture environment approximates the physiological range of native muscle tissue (approximately 2–9% $O_2$), myoglobin content increases, with oxymyoglobin predominating, thereby imparting a bright red appearance to the tissue [15]. If oxygen partial pressure is too low, myoglobin exists mainly in the deoxy myoglobin form, producing a dark-red color; if too high, rapid oxidation to metmyoglobin occurs, leading to browning [15,16]. Moreover, oxygen diffusion gradients within the cultured tissue can result in uneven pigment distribution, thereby reducing color uniformity [16].

The culture medium provides essential substrates for myoglobin synthesis. Iron sources ($Fe^{2+}$) and heme biosynthetic precursors (e.g., δ-aminolaevulinic acid, ALA) are indispensable; insufficient supply or low bioavailability leads to reduced pigment content and paler coloration [17,18]. Amino acids such as lysine and histidine not only participate in myoglobin structure but also contribute to its stability [19]. Antioxidants (e.g., vitamin E, vitamin C, glutathione) delay myoglobin oxidation, maintaining a bright and fresh appearance [17]. Energy substrates (e.g., glucose, fatty acids) indirectly influence pigment synthesis and reduction capacity by modulating cellular metabolic states [16].

Oxygen partial pressure and nutrient composition act synergistically in color formation. Adequate oxygen supply combined with sufficient pigment precursors significantly increases myoglobin content and oxygenation ratio, producing a stable, uniform color that closely resembles conventional meat. Conversely, oxygen deficiency or nutrient imbalance results in dull, uneven coloration or browning.

Future optimization of cultured meat color requires multidimensional strategies. On one hand, a systematic regulatory network integrating oxygen control, nutrient supply, and antioxidant protection should be established to achieve precise regulation of myoglobin content and chemical state. On the other hand, synthetic biology approaches—such as gene editing or metabolic engineering—may be employed to enhance myoglobin synthesis and antioxidant capacity at the cellular level, thereby improving color stability. Importantly, color regulation should not be confined to the single goal of achieving "bright red," but should also aim to replicate the diverse color characteristics of beef, pork, and poultry under various processing conditions, in order to meet heterogeneous market demands.

Most critically, these technological pathways must be integrated with sensory science and consumer research to establish a causal chain of "culture conditions→color expression→sensory pleasure."This alignment of scientific control with sensory experience will enable cultured meat to more closely approximate the holistic qualities of conventional meat.

### 3.2.2 Aroma

During the heating of cultured meat, the spectrum of volatile compounds exhibits considerable diversity and tunability, with its formation governed by multiple interacting factors. First, the composition of the culture medium not only determines the metabolic substrates available to muscle and adipocyte cells but also influences the types and proportions of precursors involved in the Maillard reaction and lipid oxidation pathways [10]. For example, media enriched in sulfur-containing amino acids promote the generation of sulfur compounds during heating, thereby imparting roasted or onion-like notes that more closely resemble conventional meat. Second, the lipid profile plays a critical role in volatile flavor formation. Variations in fatty acid composition—such as the ratio of saturated to polyunsaturated fatty acids—affect the types and concentrations of thermal degradation and oxidation products generated during heating, thereby modulating fatty, gamey, or nutty aroma characteristics [20]. Third, post-processing treatments (e.g., precooking, roasting, smoking, or high-pressure processing) interact with nutrient components to alter water activity and protein conformation [21]. These changes may either promote or inhibit specific reaction pathways, thereby regulating both the release rate of volatile compounds and the perceived intensity of aroma.

Because cultured meat lacks certain flavor precursors derived from animal metabolism, its aroma complexity may be lower than that of conventional meat. However, this limitation can be addressed by supplementing the culture system with amino acids, reducing sugars, and lipid precursors, or by employing co-culture strategies to introduce adipocytes, thereby enhancing the generation of Maillard and lipid oxidation products and improving the depth and richness of cooked aroma.

Future research should integrate gas chromatography–

ISSN 2959-409X

mass spectrometry (GC–MS) with sensory evaluation to establish quantitative models linking culture conditions, chemical composition, and sensory attributes. Such models would enable the precise design and predictive regulation of aroma in cultured meat.

## 4. Conclusion

The sensory properties of cultured meat represent one of the decisive factors influencing its market acceptance. This study has examined the key mechanisms shaping appearance, texture, and aroma, focusing on scaffold materials, oxygen partial pressure and nutrient composition of the culture medium, lipid profiles, and post-processing techniques.

Findings indicate that scaffold design must achieve a balance between mechanical performance and biocompatibility in order to promote orderly muscle fiber alignment, enhance textural complexity, and facilitate the accumulation of flavor precursors. The synergistic regulation of oxygen partial pressure and nutrient composition can significantly improve myoglobin content and color stability, thereby enhancing the visual appeal of the product. Lipid composition and nutrient supply directly influence the pathways and proportions of volatile compound formation during heating, making them critical levers for shaping aroma characteristics.

Future research should integrate multi-omics approaches (e.g., metabolomics, flavor omics) with sensory evaluation to establish quantitative models linking culture conditions, chemical composition, and sensory attributes. Such models will enable the precise design and predictive regulation of sensory quality, thereby accelerating the application of cultured meat. Dynamic bioreactors that simulate blood flow, mechanical stretching, and electrical stimulation may further promote muscle fiber maturation and myoglobin accumulation, resulting in texture and color more closely resembling those of conventional meat. In parallel, synthetic biology and metabolic engineering can be employed to direct lipid synthesis and amino acid metabolism, enabling the targeted production of key flavor precursors. Advances in materials science and 3D printing offer opportunities to develop novel biomimetic scaffolds that spatially integrate muscle fibers, adipose tissue, and vascular-like structures, thereby enhancing product complexity and realism.

At the same time, the integration of artificial intelligence with multi-omics big data will support intelligent prediction and rapid optimization of sensory quality. On the application side, cross-cultural sensory evaluation and consumer acceptance studies are essential to guide differentiated development across regional markets, while personalized product design tailored to individual nutritional needs may help reconcile health objectives with sustainability goals. As the industrialization of cultured meat progresses, it will also be necessary to establish comprehensive regulatory standards and ethical frameworks to ensure product safety, transparency, and public trust, thereby providing institutional safeguards for large-scale adoption.

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