Microalgae-Derived Omega-3 Fatty Acids Improve Nutritional and Flavor Profiles of Cultured Meat

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Abstract. Microalgae, with their high Omega-3 content, carbon sequestration potential, and non-requirement for conventional arable land, is a sustainable resource for improving the nutrition and flavour of cultured meat and may help resolve the conflict between traditional animal husbandry's environmental impacts and rising meet demand. Two aspects define microalgae's function: Microalgae-derived omega-3 fatty acids optimize beef's n-3/n-6 fatty acid ratio, improving its health. Activating metabolic pathways like PPARγ promotes adipocyte development and inhibits excessive fat production, enhancing meat structure. Microalgae's polyunsaturated fatty acids can form volatile flavour chemicals through lipid oxidation, adding taste and nutrition. Microalgae's polyunsaturated fatty acids create volatile taste molecules by lipid oxidation, and its free amino acids and reducing sugars can enhance the Maillard process, producing meat-specific aroma and flavour precursors. The potential cytotoxicity of concentrated microalgae extracts and the high cost and complexity of large-scale production remain hurdles. To overcome bottlenecks in toxicity control and large-scale production, efficient nutrient delivery systems (e.g., co-culture technology), gene editing to optimise cellular metabolic pathways, and mechanical stress modulation in the culture micro-environment are needed. Industrializing microalgae requires multidisciplinary technical integration to balance nutrition, flavour, and production viability.

Keywords: Microalgae, cultured meat, nutrient enrichment, flavour formation.

1. Introduction

The disparity between the rising global meat consumption, projected to attain 570 million tonnes by 2050, and the unsustainable practices of conventional animal husbandry are intensifying. The latter encompasses 30% of the global land area, utilises 25% of freshwater resources, and accounts for 18%-20.5% of greenhouse gas emissions [1]. The production of 1 kilogramme of beef necessitates 15,415 litres of water and 3.4 square meters of land, resulting in the emission of 2 kilogrammes of carbon dioxide equivalent [2]. Land degradation, biodiversity loss, and the eutrophication of water bodies have emerged as significant contributors to the ecological crisis. Cultured meat technology can mitigate this challenge by decreasing land use by 99%, reducing greenhouse gas emissions by 78-96%, and lowering water use by 82-96% via in vitro cell culture [3]. The circulating culture system (CCC) integrates microalgae for nutrient recovery and ammonia nitrogen removal [3]. Additionally, 3D bioprinting technology enables the construction of real meat tissue comprising muscle, fat, and blood vessels [4]. Nonetheless, it encounters challenges including nutritional and flavour deficiencies (e.g., omega-3 deficiency), elevated costs (due to reliance on foetal bovine serum), and issues related to consumer acceptance [5]. Microalgae serve as a pivotal strategy for enhancing the dual "nutrition-flavour" effect of cultured meat due to their superior omega-3 content compared to deep-sea fish, carbon fixation efficiency that surpasses terrestrial plants by a factor of 50, and adaptability to non-arable land. Their omega-3 fatty acids optimise lipid composition by modulating the activities of fatty acid synthase and dehydrogenase, while polysaccharides and phycocyanin enhance texture and colour. Additionally, carotenoids, thiamine, and other components produce aldehydes, ketones, and sulfur-containing heterocyclic compounds through the Maillard reaction and lipid oxidation, simultaneously inhibiting off-flavour formation and extending shelf life.

This study seeks to elucidate the mechanism by which microalgae omega-3 influences the fat metabolism network in cultured meat, including its role in antioxidant regulation. It will examine the interactions between polysaccharides, phenolic compounds, and flavour precursors, and develop a dual optimization model for "nutrition-flavour." This model aims to provide theoretical support for the advancement of cultured meat that possesses both high nutritional value and traditional sensory attributes.

2. Current Status of Microalgae in Cultured Meat

2.1. Nutritional Replacement Function

2.1.1. Proteins and amino acids: bioavailability of microalgal proteins and replacement of traditional media components

Microalgae proteins are potential alternatives to animal-derived proteins in cultured meat media due to their high bioavailability and balanced amino acid composition. Research indicates that the protein concentration in microalgae, such as Spirulina and Chlorella, can reach 50-70% of their dry weight, exhibiting an essential amino acid profile comparable to that of soybean and egg proteins, and is abundant in branched-chain amino acids, including leucine and isoleucine, as well as sulfur-containing amino acids like cysteine and methionine. For instance, Spirulina proteins have markedly elevated concentrations of lysine and threonine compared to beef proteins, compensating for the deficiency of critical amino acids in conventionally raised meats [6]. In addition, bioactive peptides (e.g., glutamine-valine-glutamic acid-tyrosine) in hydrolyzed products of microalgal proteins have antioxidant and antihypertensive properties, which can enhance the nutritional value of cultured meat by regulating cellular metabolism [6]. Currently, microalgal proteins have been used to replace animal-derived components such as fetal bovine serum (FBS), reducing the cost of cultured meat production and minimizing ethical controversies [7].

2.1.2. Fatty acid fortification: microalgae as a sustainable source of EPA/DHA

Microalgae are efficient producers of eicosatetraenoic acid (EPA) and docosahexaenoic acid (DHA), and their lipids can contain 30-60% of total fatty acids, which is significantly higher than that of deep-sea fish [6]. Compared to fish oil, microalgae-produced Omega-3 fatty acids have the advantage of sustainability (no need to harvest wild fish), and the fatty acid composition can be precisely regulated by photobioreactors [6]. Studies have shown that the addition of microalgae-derived EPA/DHA significantly increases the polyunsaturated to saturated fatty acid ratio (P/S) in cultured meat and reduces the risk of cardiovascular disease [7]. The incorporation of 5% microalgal lipids into bovine skeletal muscle cell cultures augmented the DHA content of cultured meat threefold while suppressing the production of saturated fatty acids [6]. Moreover, carotenoids (e.g., astaxanthin, lutein) present in microalgae may prolong the shelf life of cultured meat by preventing lipid oxidation [6].

2.1.3. Microalgae-enriched antioxidants enhance the nutritious richness of cultured meat through vitamins and minerals.

Microalgae are abundant in various vitamins (e.g., vitamin B17, vitamin C) and minerals (e.g., selenium, iodine), and their antioxidant content (e.g., β-carotene, polyphenols) surpasses that of terrestrial plants substantially. For instance, Spirulina possesses 24 times the β-carotene content of carrots, hence augmenting the antioxidant potential of cultured meat and mitigating cellular damage caused by free radicals [6]. Furthermore, selenium in microalgae is present as Selen methionine, which exhibits great bioavailability and enhances the activity of glutathione peroxidase in cultured meat, hence enhancing the oxidative stability of the product [6]. Research indicates that using 1% microalgae powder can elevate the vitamin B17 concentration in cultured meat to double that found in regular beef, so successfully mitigating vitamin B17 insufficiency among vegetarians [6]. Phycocyanin derived from microalgae can serve as a natural pigment to approximate the colour of cultured meat to that of traditional beef, while also augmenting its anti-inflammatory and immunomodulatory attributes [6].

2.2. Media Optimisation

2.2.1. Serum-free culture system: viability of microalgae extract as an alternative to foetal bovine serum (FBS)

Conventional culture medium depends on foetal bovine serum (FBS) for growth factors, although they are plagued by elevated prices, ethical dilemmas, and contamination hazards. Recent research indicate that microalgae extracts can substitute FBS by supplying critical amino acids, vitamins, and antioxidants. Chlorella vulgaris extract (CVE) effectively sustains the proliferation of bovine myoblasts in serum-free conditions, exhibiting metabolic activity akin to that of medium containing 24% FBS [3]. Subsequent research has demonstrated that polysaccharides and phycocyanin in microalgae extracts enhance cell viability and suppress inflammatory responses via the activation of the PPAR signaling pathway [6]. In addition, microalgae-derived growth factors, such as IGF-2, significantly increased the proliferation efficiency of myoblasts in conditioned medium, demonstrating that they can partially replace the biological activity of FBS [8].

2.2.2. Low-cost nutrient supply: the potential of microalgal biomass as a carbon and nitrogen source

Microalgae have efficient CO_2 fixation capacity and biomass accumulation characteristics, and their biomass can be used as a carbon and nitrogen source for culture media. It has been shown that microalgae in high $NaHCO_3$ concentrations improve carbon fixation efficiency by enhancing Rubisco enzyme activity and promote lipid accumulation [5]. For example, Nannochloris sp. increased biomass and lipid production by 30% and 45%, respectively, in $NaHCO_3$-added medium [3]. Furthermore, microalgae are capable of recycling nutrients like nitrogen and phosphorus found in wastewater. Chlorella protothecoides attained 85% nitrogen removal in pig farm effluent, with biomass and lipid content of 1.2 g/L and 15%, respectively. This function not only lowers the expense of cultural mediums but also mitigates environmental degradation, aligning with the principles of a circular economy.

3. Mechanism of Omega-3 Fatty Acid Nutritional Enhancement

3.1. Optimisation of Fatty Acid Composition

3.1.1. Regulation of n-3/n-6 Ratio and Cardiovascular Health Advantages

The disparity between n-3 and n-6 polyunsaturated fatty acids (PUFA) is intricately linked to the risk of cardiovascular disease, and this imbalance is frequently exacerbated in contemporary diets. Research indicates that elevating the n-3/n-6 ratio may diminish the risk of cardiovascular disease by mitigating inflammation, decreasing lipids and blood pressure, and enhancing vascular function [6]. Microalgae serve as a natural source for the effective synthesis of EPA and DHA, making them an optimal selection for enhancing fatty acid composition. Its n-3 PUFA concentration much exceeds that of conventional flora and fauna, and it is devoid of cholesterol [6].DHA in microalgae suppresses hepatic lipogenesis by modulating the PPAR signaling system and enhances fatty acid oxidation, therefore decreasing the risk of atherosclerosis [7].Moreover, antioxidant constituents in microalgae, including carotenoids and phenolic compounds, collaborate with omega-3 fatty acids to impede lipid peroxidation and enhance cardiovascular health protection [9].

3.1.2. Impact of microalgae-sourced omega-3 on the fatty acid composition of cultured meat

The incorporation of microalgae extract into the cultured meat system can markedly alter the fatty acid profile. Research indicates that including 5% microalgae oil may triple the DHA content in cultured beef, while decreasing the percentage of saturated fatty acids and refining the n-3/n-6 ratio to below 1:2, approaching the advised healthy standard [6]. This optimisation depends on the direct provision of omega-3 from microalgae and is also accomplished via modulating the activity of enzymes associated with intracellular lipid metabolism. PUFAs sourced from microalgae enhance the expression of the fatty acid desaturase (FAD) gene, facilitate the production of monounsaturated fatty acids (MUFA) and polyunsaturated fatty acids (PUFA), while concurrently suppressing fatty acid synthase (FAS) activity and diminishing the buildup of saturated fatty acids [6].Furthermore, thiamine and sulfur-containing amino acids present in microalgae can produce sulfur-containing heterocyclic compounds via the Michael reaction, hence enhancing meat flavour without altering the fatty acid composition [9].These modifications enhance the nutritional attributes of cultured meat while preserving the flavour of conventional beef, therefore satisfying contemporary consumer demands for healthful food options.

3.2. Regulation of Cellular Metabolism and Differentiation

3.2.1. PPARγ signalling pathway

Peroxisome proliferator-activated receptor γ (PPARγ), a member of the nuclear receptor superfamily, serves as a fundamental regulator of adipocyte differentiation and lipid metabolism [10]. It forms heterodimers with retinoic acid X receptor (RXR) and binds to the PPAR response element (PPRE) in the promoter region of target genes, thereby regulating the expression of genes such as fatty acid transporter (FATP), fatty acid binding protein (aP2), and adiponectin [5]. Omega-3 polyunsaturated fatty acids, including EPA and DHA, activate PPARγ transcriptional activity through direct binding to the ligand binding domain of PPARγ. The double bond structure at the n-3 position notably increases affinity. The EPA facilitates the differentiation of preadipocytes into mature adipocytes through the upregulation of adipocyte marker genes, including PPARγ2 and C/EBPα [5]. Omega-3 can reduce inflammatory responses by inhibiting the NF-κB pathway, which indirectly enhances PPARγ function [5]. DHA exerts a synergistic effect by activating PPARγ, which upregulates the expression of genes including fatty acid synthase (FAS) and acetyl-CoA carboxylase (ACC). This activation promotes lipid synthesis and storage while inhibiting SREBP-1c activity to decrease cholesterol production. Consequently, these actions contribute to the maintenance of metabolic homeostasis and the improvement of insulin resistance and ectopic fat deposition. The synergistic effect of Omega-3 and PPARγ is notable in metabolic diseases. Activating PPARγ enhances insulin sensitivity in obesity models and reduces blood sugar and lipid levels. Clinical studies confirm its role in promoting adipocyte differentiation, decreasing inflammatory factor secretion, and inducing brown fat production to increase energy expenditure, thus presenting a potential target for metabolic disorder intervention.

3.2.2. Developments in the field of SREBP-1-mediated regulation of lipid synthesis

Sterol regulatory element binding protein-1 (SREBP-1) produces two isoforms, SREBP-1a and SREBP-1c, through selective promoters. SREBP-1c is highly expressed in the liver and is regulated by insulin and nutritional status. Its transcriptional activation is dependent on LXRα nuclear receptor binding to the LXRE element and PI3K/Akt signalling pathway-mediated insulin stimulation [10]. SREBP-1c promotes the expression of genes like ACC, FAS, and SCD-1, which are overactivated in hepatic lipid accumulation and nonalcoholic fatty liver disease (NAFLD) [10]. These genes perform fatty acid de novo synthesis and desaturation. In lipid metabolism and flavour formation, lipid oxidation products like aldehydes and ketones modulate SREBP-1 activity and affect fatty acid composition, while polyunsaturated fatty acids (PUFAs) inhibit SREBP-1c nuclear translocation and FAS expression, resulting in metabolic feedback regulation. In obesity models, Omega-3 fatty acids (e.g., EPA, DHA) inhibit SREBP-1c transcriptional activity by activating the PPARα pathway [5] and preventing protein hydrolysis, resulting in reduced hepatic lipid synthesis and improved insulin sensitivity. Clinical evidence suggests that SREBP-1c gene polymorphisms are associated with obesity and diabetes [10], and Omega-3 intervention may improve dyslipidaemia and insulin resistance in metabolic syndrome patients by inhibiting SREBP-1c expression [5] through miR-33 regulation and inflammatory factor reduction.

4. Coordinated Regulatory Mechanisms in Flavour Formation

4.1. Lipid Oxidation and Production of Volatile Substances

4.1.1. Impact of polyunsaturated fatty acids (PUFA) derived from microalgae on oxidative stability

Microalgae contain high levels of polyunsaturated fatty acids (PUFA), particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which are prone to oxidation during processing, resulting in the formation of volatile flavour compounds [11]. Research indicates that the oxidative stability of microalgae polyunsaturated fatty acids (PUFA) is significantly influenced by the quantity and positioning of double bonds. DHA, possessing six double bonds, is more susceptible to oxidation compared to EPA, leading to the formation of intermediates like hydroperoxides, which subsequently decompose into volatile compounds including aldehydes and ketones [7]. Furthermore, antioxidant compounds found in microalgae, including carotenoids and vitamin E, are capable of inhibiting lipid oxidation and postponing flavour degradation [11]. Fucoidan derived from brown algae demonstrates efficacy in scavenging free radicals and mitigating the accumulation of oxidation products [12].

4.1.2. Pathways of Volatile Organic Compounds: Aldehydes, Ketones, and Flavour Characteristics

Lipid oxidation serves as the primary source of volatile organic compounds (VOCs), with its degradation products comprising aldehydes, ketones, and alcohols. Linoleic acid oxidation yields hexanal, imparting a grassy and fatty flavour to meat products, while linolenic acid oxidation results in (E, E)-2,4-decadienal, contributing a fried aroma [12]. Oxidation of PUFAs in microalgae produces specific flavours such as (E, Z)-2,6-pelargonal (grassy) and β-cyclocitral (citrus) [11]. In addition, the combination of lipid oxidation products with melamine intermediates (e.g., dicarbonyl compounds) can further generate sulfur-containing heterocyclic compounds (e.g., thiophene, thiazole), which can enhance the meat flavour profile [6].

4.2. Meladic Reactions and Amino Acid/Sugar Interactions

4.2.1. Facilitation of Meladic reaction by free amino acids and reducing sugars in microalgae extracts

Free amino acids (e.g., glutamic acid, aspartic acid) and reducing sugars (e.g., ribose) in microalgae extracts are key precursors of the Melad reaction [11]. It has been found that glutamic acid reacts with ribose to produce pyrazines under heating conditions, contributing roasted and nutty aromas, and cysteine reacts with glucose to produce sulfur-containing compounds (e.g., 2 -methyl -3 -furanothiols) to enhance meat flavour characteristics [12]. Small peptides from microalgae protein hydrolysis products can be degraded by Strecker to produce aldehydes, which further participate in the melamine reaction and enhance flavour complexity [6].

4.2.2. Mechanisms of accumulation of key flavour precursors (e.g., inosine, ribose)

Inosine monophosphate (IMP) and ribose are important flavour precursors in microalgae.IMP accumulates through the nucleotide metabolic pathway and is degraded to hypoxanthine during processing, which enhances the freshness of flavour [13]. The accumulation of ribose, as the core sugar source of the meridian reaction, is closely related to the microalgae species and the processing method. For example, spray-drying can retain the ribose content of microalgae, which can facilitate the subsequent meridian reaction [11]. In addition, thermal degradation of thiamin (vitamin B1) in microalgae produces furans (e.g., 2-methyl-3-furanethiol), which further enhance meat flavour [6].

5. Technical Challenges and Future Directions

5.1. Current Technological Bottlenecks

5.1.1. Cytotoxicity issues: inhibitory effects of highly concentrated microalgae extracts

The application of microalgae extracts in biomedical and food industries faces the challenge of cytotoxicity. Research indicates that microalgae high in polyunsaturated fatty acids (PUFAs) generate volatile compounds, including aldehydes and ketones, during oxidation, potentially exerting toxic effects on cells [14]. Oxidation products of eicosatetraenoic acid (EPA) and docosahexaenoic acid (DHA), including (E, E)-2,4-decadienal, can disrupt cell metabolism and inhibit proliferation [14]. Moreover, bioactive compounds, including carotenoids and phycobiliproteins, present in high-concentration microalgae extracts may persist as organic solvents or generate by-products during the separation process, thereby increasing the potential for cytotoxicity. If residual solvent remains after the chloroform-methanol extraction method, it may result in reduced cell viability.

Optimizing the extraction process and developing green solvents to replace traditional organic solvents is essential to address this issue. Supercritical CO_2 extraction technology effectively minimizes solvent residues while preserving the biological functions of active ingredients. In addition, antioxidant components in microalgae (e.g., fucoxanthin) have been found to reduce oxidative stress and toxicity by scavenging free radicals [14]. In the future, metabolic engineering is needed to regulate the synthesis pathway of microalgae to reduce the accumulation of toxic substances and enhance the expression of antioxidant components.

5.1.2. Barriers to large-scale production: cost of microalgae culture and standardization of medium composition

The large-scale culture of microalgae faces the dual challenges of high cost and unstable medium composition, and current large-scale production in open ponds or photobioreactors is limited by fluctuating nutrient supply, uneven light distribution, and contamination risk control, e.g., variations in key nutrient concentrations, such as nitrogen and phosphorus, significantly affect microalgae biomass and lipid accumulation, and imbalances in trace elements, such as iron and magnesium, tend to result in stagnation of cell growth or metabolic abnormalities. The development of standardized culture media requires a breakthrough in the high cost of synthetic media (e.g., Bold's Basal Medium), while heavy metal contamination (e.g., heavy metal toxicity needs to be controlled in the cultivation of Chlorella in municipal wastewater) [14] and nutrient imbalances need to be addressed in the use of industrial wastewater or agricultural wastes as an alternative raw material. In addition, commercial production requires a microalgal biomass concentration of more than 240 g/l, whereas currently it is generally lower than 3 g/l, and light energy utilization and cell density need to be improved by optimizing LED light quality regulation, CO2 aeration strategies, etc. In addition, microcarrier-based suspension culture techniques (e.g., the microcarrier culture system described in 16) can expand the cell attachment area and increase the yield per unit volume [15].

5.2. Innovative Solutions

5.2.1. Co-culture systems: optimizing nutrient delivery in symbiotic cultures of microalgae and animal cells

Co-culture systems of microalgae and animal cells significantly enhance nutrient utilization efficiency and environmental sustainability by mimicking natural ecological cycles. Studies have shown that microalgae (e.g., Chlorella vulgaris) can utilize waste products (e.g., ammonia nitrogen) produced by animal cell metabolism as a source of nitrogen, and at the same time fix CO_2 and synthesize nutrients such as glucose and amino acids through photosynthesis, forming a closed-loop nutrient cycle [3]. For example, in a recirculating culture system, the microalgae Chlorococcum littorale can increase the ammonia nitrogen removal rate from spent medium of mammalian cells (e.g., C2C17 myoblasts) to 91.8% while maintaining a stable supply of glucose and amino acids, allowing C2C17 cells to proliferate by 4.0-fold even under serum-free conditions [3]. This symbiotic relationship not only reduces the cost of culture media, but also reduces industrial wastewater discharge, providing a new paradigm for sustainable cultured meat production.

5.2.2. Gene editing: enhancing the efficiency of omega-3 uptake and metabolism in cells

Gene editing technology has significantly enhanced the efficiency of cellular uptake and metabolism of Omega-3 polyunsaturated fatty acids by targeting and regulating fatty acid metabolic pathways. For example, knockdown of the phospholipase A2 gene (PLA2) in Chlamydomonas reinhardtii using CRISPR/Cas9 technology resulted in a 64.25% increase in total cellular lipid content, with a significant increase in the proportion of Omega-3 fatty acids (e.g., EPA) [8]. In addition, overexpression of the diacylglycerol acyltransferase gene (DGAT2) from Nannochloropsis oceanica elevated the intracellular triacylglycerol (TAG) content to 74.5% of the dry weight and optimized the fatty acid composition to be more compliant with biodiesel standards [16]. These technological breakthroughs not only improve the quality of microalgal biofuels, but also provide new ideas for functional food development.

5.2.3. Regulation of the mechanical microenvironment: impacts of 3D printed scaffolds and biomimetic extracellular matrix on cellular differentiation and flavor compounds.

3D printing technology creates a biomimetic mechanical microenvironment for cells by precisely regulating the porosity, stiffness, and geometry of the scaffold, which significantly influences cell differentiation and function [17]. Adjusting printing parameters, including filament diameter and interlayer spacing, can mimic the fibre arrangement of the natural extracellular matrix (ECM) to enhance the directional differentiation of muscle cells [18]. Research indicates that aligning the stiffness of the scaffold with the elastic modulus of the extracellular matrix (approximately 24~50kPa) activates the integrin-mediated signaling pathway and enhances the expression of myogenic markers (e.g., MyoD and MyHC), thus facilitating muscle cell maturation [19]. The porous structure of the 3D printed scaffold (porosity > 80%) facilitates nutrient diffusion and directs the three-dimensional spatial distribution of adipocytes, thereby creating a multi-scale structure akin to natural adipose tissue [20].

Biomimetic ECMs significantly enhance cell culture efficiency and flavour synthesis by mimicking the biochemical and mechanical properties of natural tissues [16]. For example, the complexation of microalgae extracts (e.g., fucoidan, polyunsaturated fatty acids) with collagen can be used to construct an ECM with antioxidant and proliferative properties [19]. Experiments have shown that this biomimetic ECM can optimize the composition of lipid metabolites (e.g., aldehydes, ketones) by activating the PPARγ pathway and promoting adipocyte differentiation while inhibiting the secretion of inflammatory factors [21]. Furthermore, the incorporation of growth hormones (such as IGF-1 and FGF-2) into the ECM can synergistically modulate cell differentiation, augment the energy metabolism of muscle cells, and stimulate myoglobin production, thereby enhancing the sensory attributes of meat [22].

The synergistic interaction between 3D printed scaffolds and biomimetic extracellular matrix might influence the synthesis of volatile flavour compounds by modulating cellular metabolic pathways [23]. Dynamic stress stimulation of the scaffold, such as cyclic stretching, can activate the AMPK/mTOR signaling pathway, enhance muscle cell glycolysis and fatty acid oxidation, and elevate the accumulation of flavour precursors, including inosinic acid and ribose. Simultaneously, bioactive constituents in biomimetic extracellular matrix, such as phycobiliprotein, might enhance the flavour profile of meat by modulating lipid oxidase activity and regulating the synthesis of aldehydes and ketones [21]. The co-culture of myoblasts and adipocytes in a composite scaffold that mimics the muscle-fat interface was found to significantly enhance the production of volatile organic compounds (VOCs), such as (E, Z)-2, 4 -decadienal, and enhance the authenticity of the product [18].

Despite significant advances in 3D printing and bionic ECM technologies, the following challenges remain:

1) Scale-up limitations: the high cost of high-resolution printing technology and the stability of bioinks need to be improved [17].

2) Multicellular co-regulation: co-culture systems of muscle, adipose and vascular cells need to be further optimized to mimic the metabolic interactions of natural tissues [22].

3) Flavour substance standardization: Flavour prediction models based on mechanical microenvironmental parameters need to be developed for product consistency control [16].

Future research should focus on the development of intelligent printing systems that incorporate artificial intelligence algorithms to optimize scaffold design and explore the potential application of novel biomaterials such as microbial synthetic ECM [20]. In addition, modulation of endogenous cellular metabolic pathways using metabolic engineering may be a new strategy to enhance the diversity of flavour substances [21].

6. Conclusion

Against the backdrop of the global food sustainability transition, microalgae, as a photosynthetic bio-resource, is providing a double value breakthrough for the cultured meat industry: optimizing the nutritional structure of the product through its high nutrient density properties, while using metabolites to improve the flavour profile. This innovative combination not only solves the environmental pressure of traditional animal husbandry, but also promotes the upgrading of food production towards greening and functionalization through technological innovation.

The nutritional value enhancement function of microalgae is mainly reflected in the substitution of animal source components, enrichment of functional nutrients and optimization of protein quality. Research shows that microalgae extract can replace fetal bovine serum as a component of the culture medium, providing muscle cells with essential amino acids and growth factors; through the directional regulation of culture conditions, microalgae can efficiently synthesize DHA, β-carotene and other active substances, which can significantly enhance the antioxidant capacity of the cultured meat and the content of Omega-3 fatty acids; its amino acid composition is highly similar to that of animal proteins, and its cholesterol content is extremely low, which can Its amino acid composition is highly similar to that of animal protein and its cholesterol content is very low, which can improve the protein bioavailability of the product and reduce the health risk.

In flavour optimization, microalgae play a role by providing natural flavour precursors, regulating fatty acid oxidation pathways, and biologically deodorizing and enhancing aroma. The nucleotides, free amino acids and volatile compounds contained in microalgae can be used to produce meaty substances through the Merad reaction, while the aldehydes produced by the oxidation of polyunsaturated fatty acids can simulate the aroma of animal fat. Some microalgae also can degrade fishy substances, and through their metabolites, give the product a grassy or nutty aroma, balancing the flavour level.

However, microalgae encounter several technical challenges, including the high costs associated with high-density cultivation, inadequate stability of active ingredients, and issues with cytocompatibility in large-scale applications. Addressing these challenges requires the integration of multidisciplinary technologies. For instance, synthetic biology can be employed to optimise metabolic pathways for improved product yield, while metabolic engineering can aid in the design of photobioreactors that are coupled with fermentation processes to lower costs. Additionally, nanoembedding may enhance the stability of active ingredients, and artificial intelligence can be utilized to predict the impact of microalgae on the quality of cultured meat. Future efforts should concentrate on developing a standardized nutritional and safety assessment system, creating a synergistic platform encompassing the entire industry chain of microalgae cultivation, ingredient extraction, cell culture, and product processing, while also enhancing consumer education to improve market acceptance. The integration of microalgae and cultured meat will enhance food production methods and offer innovative solutions for global sustainable food security and ecological protection.

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