



Microalgal biomass in the European food industry: navigating regulation, technological innovation, and consumer acceptance[☆]

Francesca Girotto^{*}, Alessandro Scapini

Department of Environmental Science and Policy, Università degli Studi di Milano, Via Mangiagalli 25, 20133 Milano, Italy

ARTICLE INFO

Keywords:

Microalgae-based foods
Functional ingredients
Novel foods EU
Consumer acceptance

ABSTRACT

The growing need for sustainable and nutrient-dense food sources has positioned microalgae as a promising ingredient for the food industry. Rich in high-quality proteins, essential fatty acids, vitamins, and bioactive compounds, microalgae hold great potential as functional ingredients in the development of health-promoting food products. However, regulatory, technological, and consumer-related barriers still limit their widespread adoption in Western countries. While certain species have a history of consumption, many still require approval under the EU Novel Food Regulation before commercialization. Additionally, processing and formulation challenges arise due to protein interactions, water absorption dynamics, bioaccessibility constraints, and final sensory attributes, as their strong pigmentation and marine-like flavours can impact consumer acceptance. Studies confirm that low incorporation levels ($\leq 3\%$) generally maintain favourable sensory properties in staple products. Among emerging applications, meat analogues represent a particularly promising area, where the novelty of the product category allows for more flexible taste expectations and sensory reinterpretation, although limitations in texturization remain. Sensory optimization strategies, including encapsulation and flavour masking, are being explored to enhance palatability, while pulsed electric field, mechanical (i.e., ultrasounds, high-pressure homogenization) and enzymatic treatments are being implemented to improve nutrients absorption. Although food neophobia, dietary habits, and cost remain key barriers to consumer acceptance of microalgae-based foods, neuromarketing approaches offer promising tools to influence perception and encourage adoption. Advances in cultivation efficiency, genetic engineering, formulation and processing techniques are progressively improving scalability, affordability, and sensory appeal, paving the way for microalgae to evolve from niche applications to mainstream food alternatives.

1. Introduction

The increasing demand for food security in the face of population growth and climate change presents one of the most urgent challenges of our time. Food systems contribute approximately 30 % of global greenhouse gas (GHG) emissions while simultaneously being highly vulnerable to environmental shifts that impact food availability, access, utilization, and resilience [1]. With the global population projected to exceed 10 billion by 2050, ensuring sustainable food systems is a priority [2].

A key strategy in this transition is the diversification of protein sources, reducing reliance on environmentally intensive livestock farming. Among alternative proteins, microalgae have emerged as a promising and sustainable option due to their exceptional nutritional

profile (e.g. 30–70 % protein content), rapid growth cycle (1–2 weeks) and low environmental footprint [3,4]. For instance, their ability to grow without the need for fertile soil further enhances their sustainability credentials.

Microalgae are a phylogenetically diverse group of microorganisms, many of which are primarily photoautotrophic, although certain species can switch to heterotrophic or mixotrophic modes depending on environmental conditions. Certain microalgal species have demonstrated the ability to synthesize a variety of nutritionally relevant compounds, including essential fatty acids, vitamins, and other bioactives, although the type and concentration of these metabolites can vary considerably across taxa [5]. For instance, some microalgae are currently utilized as biofactories for the production of omega-3 polyunsaturated fatty acids (PUFAs), with particular emphasis on eicosapentaenoic acid (EPA, 20:5)

[☆] This article is part of a Special issue entitled: 'Current Reviews 2025' published in Algal Research.

^{*} Corresponding author.

E-mail address: francesca.girotto@unimi.it (F. Girotto).

and docosahexaenoic acid (DHA, 22:6), which are recognized for their essential role in human health [6], as well as on alpha-linolenic acid and other essential fatty acids such as gamma-linolenic acid [7]. Among these, *Schizochytrium* (Thraustochytriaceae, Labyrinthulomycota) stands out for its high DHA and EPA content combined with robust biomass productivity [7]. *Nannochloropsis* (Ochrophyta) and *Cryptocodinium cohnii* (Dinoflagellata) are also widely known for its PUFAs profile [8].

Unlike macroalgae, which are commonly consumed whole in traditional Asian cuisines [9], microalgae are increasingly studied for their incorporation as functional ingredients in modern food systems.

Despite their potential [10], challenges remain in scaling up production, optimizing processing techniques, and improving consumer acceptance. Overcoming these barriers requires continued research, technological advancements, and strategic investment in the alternative protein industry. This review aims to analyse the most relevant aspects of microalgae in the food sector, focusing on regulatory frameworks, growth conditions, formulation challenges, and consumer acceptability. However, it does not delve into the broader field of bioactive compounds extractable from microalgal biomass.

2. Microalgae: how biological diversity influence their use in the food sector

Microalgae represent a polyphyletic group of unicellular, photosynthetic organisms, i.e., organisms that share similar functional traits but derive from distinct evolutionary lineages and do not share a single common ancestor. This includes both eukaryotic microalgae (Eukarya) and photosynthetic prokaryotes, namely cyanobacteria (Bacteria) [11]. Despite their fundamental differences, both groups share biotechnological relevance and are increasingly utilized in food applications [12].

However, among the hundreds of thousands of estimated species, only a limited number are commercially exploited in the food industry (see Table 1) [5], or in nutraceutical and cosmetic ones [16,31]. This restricted use can be mainly attributed to the significant barriers posed by safety and regulatory requirements [10,32]. For a species to be authorized for human consumption, it must undergo rigorous toxicological evaluation, nutritional profiling, and demonstration of absence of contaminants or harmful metabolites. Additionally, large-scale cultivation demands extensive optimization to ensure stable growth, high yields, and consistent composition.

Microalgae are broadly categorized into several major phyla or classes, with taxonomic grouping varying depending on phylogenetic and structural criteria. Chlorophyta, such as *Chlorella vulgaris*, *Dunaliella salina*, and *Haematococcus pluvialis*, represent the most commercially relevant eukaryotic microalgae, valued for their pigments and antioxidants. Similarly, Bacillariophyta, or diatoms, are eukaryotic but characterized by silica-based cell walls, which complicate their direct use in food but make them a valuable source of omega-3 fatty acids. Ochrophyta, including certain golden algae species, have potential in food applications but are currently less exploited compared to Chlorophyta. In contrast, Cyanobacteria, formerly known as blue-green algae, are prokaryotic and include *Limnospira* sp. (formerly *Arthrospira platensis*, commonly known as Spirulina), one of the most widely consumed microalgal species and noted for having one of the highest protein contents. Unlike eukaryotic microalgae, cyanobacteria possess a peptidoglycan-based cell wall and lack rigid cellulose structures, which enhances digestibility and facilitates whole-biomass applications [33,34].

The structural differences between eukaryotic microalgae and cyanobacteria have significant implications for their food processing and bioaccessibility. Eukaryotic microalgae, with their membrane-bound

Table 1

Comparison of the most widely cultivated and commercialized edible microalgae species (as whole biomass) including a complete list of those authorized or exempt under Regulation (EU) 2015/2283 [13,14].

Microalgae species	Morphological characteristics	Protein content (% dw)	Notable compounds	References
Widely cultivated and commercialized				
<i>Limnospira</i> sp. - <i>platensis</i> , <i>maxima</i> , <i>fusiformis</i> , <i>indica</i>	Filamentous Cyanobacterium	55–70	Proteins, essential amino acids (EAA), phycocyanin, vitamins	[15]; [5]
<i>Chlorella vulgaris</i>	Spherical, non-flagellated, unicellular Chlorophyta	38–58	β-1,3-glucan, EAA	[16]; [17]
<i>Dunaliella salina</i>	Oval-shaped, biflagellated, unicellular Chlorophyta	49–57	β-Carotene, antioxidants	[18]; [19]
<i>Haematococcus pluvialis</i>	biflagellated, unicellular Chlorophyta with non-motile cyst stage under stress	35–40	astaxanthin	[18]; [19]
Minor				
<i>Aphanizomenon flos-aquae</i>	Filamentous Cyanobacterium with straight or curved trichomes	60–70 %	Omega-3 PUFAs, C-phycocyanin, β-phenylethylamine	[20]
<i>Auxenochlorella protothecoides</i>	Spherical, non-flagellated, unicellular Chlorophyta	42–55 %	PUFAs, chlorophylls, vitamins	[143]
<i>Auxenochlorella pyrenoidosa</i>	Spherical, non-flagellated, unicellular Chlorophyta	51–58 %	EAA, Iron, vitamin B12, anticancer peptides	[144]
<i>Chlorella sorokiniana</i>	Spherical, non-flagellated, unicellular Chlorophyta	45–50 %	EAA, antioxidants	[21]
<i>Chlorella pyrenoidosa</i>	Spherical, non-flagellated, unicellular Chlorophyta	49–57 %	Vitamin B12, iron, lutein	[22]
<i>Jaagichlorella luteoviridis</i>	Spherical to ellipsoidal, non-flagellated, unicellular Chlorophyta	28–47 %	Carotenoids, chlorophyll, calcium, vitamins B1, B2	[23]
<i>Parachlorella kessleri</i>	Spherical, non-flagellated, unicellular Chlorophyta	41–54 %	Omega-3 PUFAs, β-carotenoids, antioxidants	[24]
<i>Graesiella emersonii</i>	Spherical to ellipsoidal, non-flagellated, unicellular Chlorophyta with double-layered cell wall	47–66 %	Omega-3 PUFAs	[25]
<i>Scenedesmus</i> sp.	Non-flagellated, colonial Chlorophyta	50–56 %	PUFAs, chlorophyll, phenolics	[22]
<i>Tetraselmis chuii</i>	Elliptical, slightly flattened, 4-flagellated, unicellular, theca-covered Chlorophyta	40–65 %	EAA, carotenoids, PUFAs	[26]
<i>Rhodomonas salina</i>	Oval-shaped, flagellated, unicellular Cryptophyta	33–64 %	EPA, DHA	[27]
<i>Euglena gracilis</i>	Elongated, flagellated, unicellular Euglenozoa	39–61 %	Paramylon, vitamins E, C	[22]
<i>Nannochloropsis</i> sp.	Spherical, non-flagellated, unicellular Ochrophyta	30–43 %	EPA	[28]
<i>Odontella aurita</i>	Rectangular with rounded ends, yellow-brown, unicellular (chain-forming) Ochrophyta with silicified cell wall	25–48 %	EPA, fucoxanthin, silica, chrysolaminarin	[24]
<i>Schizochytrium</i> sp.	Spherical, non-flagellated, unicellular (can form aggregates) Labyrinthulomycota	12–18 %	DHA, EPA	[29]
<i>Ulkenia</i> sp.	Spherical to irregular, unicellular Labyrinthulomycota	10–15 %*	DHA, EPA, astaxanthin	[30]

* This value refers to the protein content as a percentage of the dry weight of exopolysaccharides, not of the total biomass.

organelles and cellulose-rich cell walls, often require mechanical, enzymatic, or thermal processing to enhance digestibility and nutrient absorption. This additional processing increases production costs but allows for the extraction of high-value compounds, such as astaxanthin from *Haematococcus pluvialis* and β -carotene from *Dunaliella salina*, which are widely used as natural food additives. In contrast, cyanobacteria such as *Spirulina* possess a relatively simple cell wall structure lacking cellulose, which facilitates digestion and enables direct consumption in powder or tablet form without the need for mechanical or enzymatic cell disruption. This feature can make them more cost-effective for large-scale food applications. However, actual bioaccessibility depends on multiple factors, including processing methods [35], the specific strain used, and interactions with the food matrix when incorporated as an ingredient, all of which can influence the release and bioaccessibility of nutrients in the human body.

Additionally, microalgae exhibit diverse metabolic strategies that influence their nutritional composition and scalability. Autotrophic microalgae rely on light and CO_2 for growth, making them highly sustainable but dependent on environmental conditions. Some microalgal species can be cultivated heterotrophically using organic carbon sources, which enables higher biomass yields in controlled environments, albeit the higher initial investment and operational costs compared to autotrophic systems. Mixotrophic microalgae combine both strategies, offering metabolic flexibility that can optimize nutrients synthesis [36]. The adaptability of microalgae to freshwater, marine, brackish, and even wastewater environments further reinforces their potential as sustainable food sources, while photosynthetic growth contributes to short-term carbon sequestration, which can support environmentally conscious food production systems [12].

2.1. Microalgae production

2.1.1. Cultivation and harvesting

The industrial production of microalgae consists of two major stages: upstream processing - including medium preparation, inoculum development, and biomass cultivation; and downstream processing - covering harvesting and post-processing [37].

The metabolic plasticity of microalgae allows indirect manipulation of biosynthetic pathways through controlled changes in environmental and nutritional conditions, enabling the targeted production of specific nutrients [34]. The culture medium plays a critical role in determining biomass yield and biochemical composition, thereby influencing the accumulation of high-value compounds [38]. While in autotrophic systems, pH, light, and temperature regulation are the primary factors influencing growth, heterotrophic systems require external carbon sources such as molasses or glucose. Innovative approaches, including CO_2 -derived feedstock from industrial emissions and food waste streams, are emerging as sustainable alternatives [39,40]. A key challenge in microalgal cultivation is enhancing protein content and reaching a well-balanced content of unsaturated fatty acids (UFAs). Several strategies have shown success. The concentration-shift method, for instance, has proven effective in heterotrophic *Chlorella vulgaris*. Xie et al. [41] demonstrated that the observed increase in protein accumulation is likely due to a molecular 'priming' effect: during the initial nitrogen-starvation phase, specific genes related to nitrogen assimilation are sensitized, enabling the cells to rapidly and efficiently take up and incorporate nitrogen once it becomes available again. This transcriptional readiness may underlie the enhanced protein biosynthesis upon refeeding. Additionally, crude glycerol, a by-product of biodiesel production, has been found to increase protein yield in *Spirulina* cultures by serving as an efficient carbon source [42]. Maintaining a temperature slightly below the optimal set-point for each strain has been shown to enhance the synthesis of PUFAs, such as EPA and DHA. Lower cultivation temperatures reduce the synthesis of saturated fatty acids while increasing UFAs concentrations, likely due to temperature-induced limitations in nitrogen uptake [43] and temperature-dependent

regulation of desaturase enzymes involved in their biosynthesis [44]. However, each culture must be carefully optimized to achieve a balanced trade-off between protein content and UFAs accumulation.

Microalgae production primarily occurs in open or closed cultivation systems (Table 2), each with distinct advantages and challenges:

- Open systems (raceway ponds, tanks, thin layer cascades): are cost-effective and energy-efficient but vulnerable to environmental fluctuations, contamination, and low productivity. For example, the exposure to airborne pollutants, heavy metals, and pathogenic microorganisms poses challenges for food safety compliance, especially when minimal downstream processing is applied. They are commonly used for large-scale biomass production, particularly for *Spirulina* due to its ability to thrive in highly alkaline environments (pH ~9–11), which naturally inhibits unwanted microorganisms [16]. Similarly, *Dunaliella salina* is well-suited for open systems because of its halophilic nature, allowing it to grow in high-salinity conditions that reduce microbial competition. Open pond systems using natural sunlight typically reach biomass concentrations of ~0.5–1.5 g/L [50].
- Closed systems (photo-bioreactors - PBRs, fermenters): provide controlled environments that minimize contamination risks and optimize nutrient uptake. They offer better suitability for regulatory approval, facilitating compliance with EU Novel Food requirements, ensuring greater consistency (in terms of biochemical composition), traceability, and food safety standards. These systems are preferable for species cultivated for high-value compounds like astaxanthin, β -carotene, and omega-3 fatty acids [4,51]. *Chlorella* sp. are particularly prone to contamination, while *Haematococcus pluvialis* requires high-purity conditions for astaxanthin accumulation, hence both are predominantly cultivated in closed systems to ensure quality and consistency. PBRs can typically achieve yields up to ~6 g/L, though in heterotrophic fermenters, more than double this biomass density can be obtained under optimal conditions, benefiting not only from improved temperature control (25–35 °C according to the species) and light availability but also from the ability to precisely control light wavelength and intensity [47]. Indeed, the light spectrum can be optimized to enhance growth efficiency. For instance, a mix of red and blue LED light has been shown to increase astaxanthin in *Haematococcus pluvialis* [52], while blue light was found effective in accelerating the growth cycle of *Spirulina* [53]. Best light intensities have been reported to be between 50 and 400 $\mu\text{mol}_{\text{photons}}\text{m}^{-2}\text{s}^{-1}$ [54].

The efficiency of production varies greatly: to obtain the same biomass yield, an open raceway pond requires approximately 300 m^2 , whereas a PBR requires only 25 m^2 , and a fermenter as little as 2.5 m^2 [55]. Hybrid approaches, such as starting in PBRs and transitioning to open ponds, are also used to optimize production, as seen in the cultivation of *Haematococcus pluvialis* [56].

Once the desired biomass concentration is reached, downstream processing begins, covering harvesting, dewatering, and drying. These steps are energy-intensive and impact overall production costs [37]. Harvesting, which accounts for 20–30 % of total production costs due to low biomass concentrations and small cell sizes [38], is performed through centrifugation (highly efficient but costly), filtration (used for larger species such as *Spirulina*) or flocculation (cost-effective and energy-efficient, using chemical or biological agents to aggregate cells) [57]. Gentler technologies including bioflocculation, electrolytic coagulation, ultrasonic aggregation, magnetic separation and phototaxis are compatible with food-grade microalgae production [58]. Among these, bioflocculation, either via exopolysaccharide-secreting bacteria (e.g., *Bacillus*, *Pseudomonas*, *Paenibacillus*) or via filamentous fungi (e.g., *Aspergillus*, *Trichoderma*) that form entangled aggregates, is increasingly recognized as an eco-friendly and low-cost alternative [58].

Table 2

Comparison of open vs. closed microalgae cultivation systems and autotrophic vs. heterotrophic cultivation modes for food applications: key considerations.

	Advantages	Disadvantages	Production costs	References
Open Systems	Lower capital and operational costs; utilizes natural sunlight, reducing energy expenses; easier scalability for bulk production; suitable for species like <i>Spirulina</i> and <i>Dunaliella</i>	High vulnerability to contamination; limited environmental control (temperature, pH, CO ₂ , nutrients), leading to variable nutritional composition; lower biomass densities (typically 0.5–1.5 g/L); higher water evaporation and space requirements	0.30–5.00 USD/kg dry biomass (depending on system efficiency and species)	[45,46]
Closed Systems	Higher biomass densities (from ~6 g/L in PBRs up to greater densities in fermenters) precise environmental control (temperature, CO ₂ , nutrients, light intensity); reduced contamination risks; more efficient nutrient and gas exchange; year-round production; suitable for high-value products (e.g., <i>Haematococcus</i> , <i>Chlorella</i>)	High investment and operational costs; requires artificial lighting or advanced light modulation; energy-intensive for cooling and gas/air exchange; greater complexity, with potential technical failures	2.50–12.00 USD/kg dry biomass USD/kg dry biomass (higher costs due to infrastructure and energy demands)	[45]; [47]

	Advantages	Disadvantages	Key sustainability strategies	References
Autotrophic growth	Final product enriched with several nutritionally valuable bioactives	Accumulation of pigments (e.g., chlorophylls) and release of light-dependent volatile organic compounds	Use of industrial CO ₂ emissions as carbon feedstock	[48]; [49]
Heterotrophic growth	Final product with a more neutral sensory profile	Reduced diversity of secondary metabolites due to absence of light	Use of non-virgin organic carbon sources (from side-, waste-streams)	[48]; [49]

2.1.2. Drying process

The harvested microalgae biomass can either be sold in frozen form or subjected to further processing. Drying is a critical step for preserving nutritional quality while ensuring product shelf-life, but it remains one of the most energy-intensive stages, often accounting for over 50 % of the total energy consumption in microalgae production [55,59] and in some cases up to 75 % [60]. Freeze-drying preserves nutrients but is highly energy-intensive, whereas thermal drying (e.g., sun drying, convective drying) is more cost-effective but may degrade heat-sensitive compounds [38]. Microwave and spray drying are currently the most cost-efficient options, offering a good balance between energy use and biomass integrity. However, their optimization must always be tailored to the specific strain to ensure the stability of the powder during storage. The combination of osmotic dehydration with advanced non-thermal techniques, such as pulsed electric fields (PEF), microwave drying, ultrasound-assisted treatments, and pulsed vacuum applications, represents an innovative approach for the processing of microalgae, although it still requires further investigation. However, these hybrid strategies remain at a largely experimental stage and require further research to validate their scalability, efficacy, and applicability to different microalgal species. These methods offer a milder alternative to conventional drying, effectively minimizing oxidation and preserving heat- and oxygen-sensitive compounds like polyunsaturated fatty acids, pigments, and volatile aroma molecules. From a sensory standpoint, such integrated strategies contribute to maintaining the natural colour of the biomass and reducing the development of off-flavours and unpleasant odours, often caused by the oxidative degradation of lipids and sulphur-containing compounds [61]. Despite their potential, these approaches have been primarily investigated in fruits and vegetables, while their application to microalgae remains largely underexplored. Future research should also focus on evaluating their impact on the sensory profile of the final microalgal ingredient, particularly in terms of key flavour-active compounds preservation such as amino acids, organic acids, and volatile molecules responsible for taste and aroma. Electrohydrodynamic (EHD) drying represents another promising non-thermal technique for the dehydration of microalgal biomass, particularly suited for heat-sensitive compounds. By applying a high-voltage electric field (typically 1–10 kV/cm) between emitter and collector electrodes, EHD induces corona discharge and generates a localized ionic wind, which drives moisture removal without the need for elevated temperatures [35]. This can help preserve the nutritional integrity and bioactivity of

microalgal compounds. While EHD has not yet been widely applied to microalgae, its low energy consumption (1–10 W) and capacity to reduce drying time and shrinkage, while enhancing rehydration and texture, make it an attractive alternative to conventional drying methods. Recent modelling work by Defraeye and Martynenko [62] demonstrated that the wire-to-mesh electrode configuration ensures more uniform drying across multiple food products, minimizing vapour recirculation and enabling scalability, an insight particularly relevant for dense microalgal biomass systems. Thus, EHD holds strong potential for microalgae valorization, pending further experimental validation on algal matrices.

Overall, achieving sustainability in microalgae production requires balancing economic feasibility with environmental responsibility. This includes minimizing GHG emissions, water usage, and ecotoxicity while maximizing protein productivity. Although closed systems allow year-round, contamination-free production, open systems are still favoured for large-scale applications due to their lower energy demands [63].

2.1.3. Cultivation-related sustainability considerations

A recent comparative analysis of fourteen protein sources revealed that microalgae, despite their high nutrient density, exhibit comparatively high energy and water demands, which contribute to their lower ranking in overall environmental impact [64]. However, they performed well in terms of land use efficiency, ranking sixth, and achieved a ninth-place position in the combined Nutritionally Invested Environmental Impact index, due to their rich nutritional profile. These results suggest that, while current cultivation systems are still resource-intensive, microalgae could play a strategic role in future food systems, particularly as high-value ingredients, if technological advancements succeed in reducing their environmental footprint [64]. Therefore, reducing the environmental burdens associated with the cultivation stage emerges as a key priority for enhancing the overall sustainability of microalgal production. Since cultivation is the most resource-intensive phase in the life cycle of microalgae, improvements in system design, energy sourcing, and nutrient management could significantly mitigate impacts and unlock the full potential of microalgae as sustainable protein sources.

From a life cycle perspective, the environmental impacts of microalgal production strongly depend on the chosen mode of cultivation (Fig. 1). In autotrophic systems, the primary burdens are associated with energy and heat consumption, while in heterotrophic systems, the most significant impacts are related to the use of glucose as a carbon source.

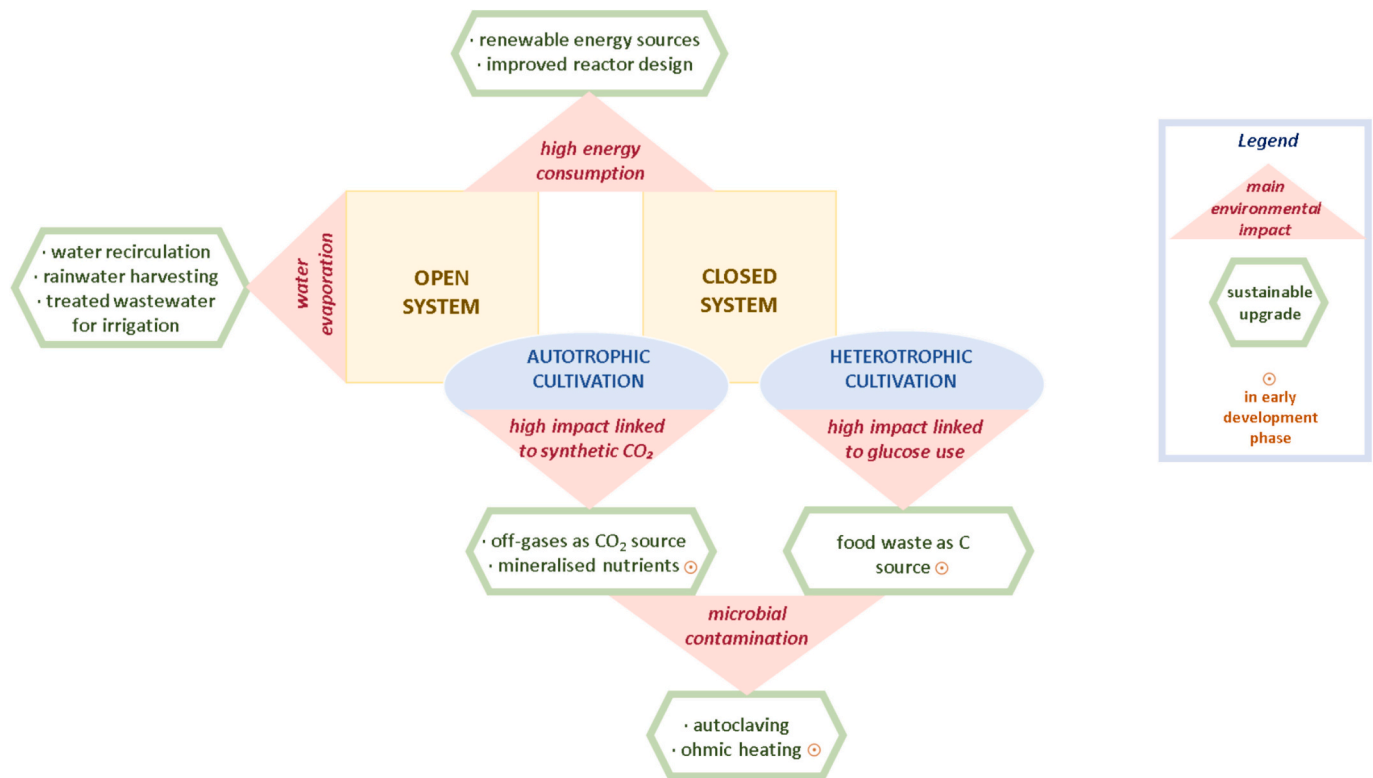


Fig. 1. Schematic overview of the main environmental hotspots and potential sustainability-enhancing strategies in microalgal cultivation systems for food-grade biomass production.

According to Smetana et al. [55], heterotrophic cultivation in closed fermenters has the potential to reduce the environmental impacts observed in both open raceway ponds and closed photobioreactors. In their comparative LCA study, using a common output of 1.4–1.8 tons of dry biomass per year, the highest impact was reported for open ponds (300 m³, 7.7–9.7 mPt), followed by photobioreactors (25 m³, 4–4.7 mPt), with the lowest impact observed for heterotrophic systems (2.5 m³, 0.4 mPt). Here, “mPt” refers to millipoints in the Eco-indicator 99 system, where 1000 Pt equals the average annual impact of a European citizen.

Regardless of the cultivation method, sustainability can be significantly improved through the use of renewable energy sources, such as photovoltaic systems [65]. In parallel, improvements in photobioreactor design can also enhance energy efficiency. For example, Schade and Meier [66] demonstrated that reducing the tube diameter in tubular photobioreactor systems increased volumetric productivity. Although areal productivity remained unchanged, this configuration reduced electricity demand and water use per unit of biomass. However, these benefits were confirmed only for *Nannochloropsis* sp. and *Phaeodactylum tricornutum*, highlighting the need for further validation across diverse microalgal strains. Indeed, higher biomass concentrations in smaller volumes may not universally translate into performance gains, and could introduce strain-specific physiological constraints.

Open systems, while simpler, are also characterized by high water consumption due to evaporation. In fact, evaporation from raceway ponds represents the main driver of freshwater loss [67]. Water-saving strategies such as internal water recirculation, recovery of treated wastewater for irrigation, and rainwater harvesting for external cleaning and cooling could save tens of cubic meters of freshwater annually [67].

Autotrophic cultivation can also benefit from the use of industrial waste CO₂ streams instead of synthetically produced CO₂. Porcelli et al. [68] reported that replacing synthetic CO₂ with waste CO₂ from biogas upgrading led to a significant improvement in the system's environmental profile, particularly in terms of GHG emissions. Furthermore,

special photobioreactor configurations have been explored to enable the indirect use of waste-derived organic substrates under autotrophic conditions. In such systems, organic matter is mineralised in a separate biofilter compartment, and the resulting nutrients diffuse across a semi-permeable barrier into the photobioreactor, supporting photoautotrophic growth [39].

On the other hand, the environmental footprint of heterotrophic systems could be further reduced by replacing glucose whose use poses challenges in terms of cost and competition with food crops. This has prompted growing interest in alternative carbon sources such as dairy whey, molasses, banana pulp, and confectionary waste [69]. These substrates have demonstrated comparable biomass yields and may significantly reduce operational costs [69,70].

However, when applying waste streams, either as CO₂ or organic carbon, microbial contamination remains a critical concern, especially when the biomass is intended for food use. Maintaining sterile conditions thus remains a major operational challenge, as contamination by fast-growing bacteria can compromise cultures and contribute up to 30 % of total production costs [69,71]. Marques et al. [72] evaluated different pre-treatment methods of food waste, including conventional heating, ohmic heating, and autoclaving, to assess their ability to sanitize the substrate and preserve its carbon content for use in heterotrophic microalgae cultivation. Autoclaving completely eliminated microbial contamination while increasing the concentration of reducing sugars [72]. Although ohmic heating also achieved high microbial inactivation in shorter time and at lower temperatures, it led to a significant reduction in sugar content, which could compromise the carbon availability for microalgal growth.

3. Legislative framework: edible microalgae within the European Union

In the European Union (EU), the commercialization and use of microalgae as food or food ingredients are subject to a comprehensive

regulatory framework aimed at ensuring food safety and consumer protection. The EU's food safety policy follows the “farm to fork” approach, regulating the entire food chain, including products imported from non-EU countries. The European Food Safety Authority (EFSA) plays a crucial role in assessing risks associated with food products by carefully examining a detailed dossier submitted by each applicant, and offering scientific advice to the European Commission, the European Parliament, and Member States to support decision-making processes [73]. Specifically, this dossier must include detailed information on the identity of the organism, production process, compositional data, proposed uses, toxicological studies, and mutagenicity and safety assessments. Following EFSA's scientific opinion, the final authorization is issued by the European Commission and leads to the inclusion of the product in the Union List. Due to the complexity, cost, and duration of this process, market access has so far been granted only to well-characterized and extensively studied species, with regulatory approvals distinguishing between those authorized solely for extract-based applications and those approved for incorporation as whole biomass.

The foundational regulation governing all food products in the EU is the General Food Law (Regulation (EC) 178/2002), which establishes key principles such as risk assessment, food safety, and consumer protection [74]. In addition to these statutory requirements, other regulations apply to microalgal food products, particularly in areas of hygiene, contaminants, labelling, and official controls [75], specifically Regulation (EC) 852/2004 on hygiene requirements for food business operators; Regulation (EC) 1831/2003 setting maximum levels for contaminants in foodstuffs; Regulation (EU) 1169/2011 on food information and labelling requirements; Regulation (EU) 2017/625 on official controls for food law compliance; Regulation (EC) 2019/1381 on transparency in the EU risk assessment process.

Despite some microalgae species having a history of food use, many are classified as Novel Foods (NF) under Regulation (EU) 2015/2283 [76]. Novel Foods are defined as foods that were not consumed to a significant degree within the EU before May 15, 1997. The regulation modernized the previous Regulation (EU) 258/97, streamlining the approval process for NF while maintaining strict safety assessments [32]. For a food product to qualify as a NF, it must fit into at least one of the ten categories listed in Article 3 of the regulation. In the case of microalgae, the most relevant categories include Article 3(2)(a)(ii): “Food consisting of, isolated from, or produced from microorganisms, fungi, or algae” and Article 3(2)(a)(iv): “Food derived from cell or tissue cultures of plants, microorganisms, fungi, or algae”.

Approved NF are included in the Union List, established under Commission Implementing Regulation (EU) 2017/2470, detailing permitted microalgae-based food products, their usage conditions, and

labelling requirements. Table 3 provides a structured overview of microalgal products classified under the NF Regulation.

Finally, the Novel Food Catalogue (NFC), managed by the European Commission, provides a useful reference for the classification of microalgae, where they are categorized as follows [14]:

- Not Novel in Food: already consumed in the EU before 1997 and does not require authorization (e.g., *Spirulina*);
- Not Novel in Food Supplements: used in food supplements before 1997 (e.g., *Haematococcus*);
- Authorized Novel Food: approved and listed in the Union List (e.g., *Tetraselmis*);
- Novel Food: requires authorization due to lack of significant consumption before 1997;
- Subject to Consultation Request: its status is under evaluation.

The EU's regulatory framework for edible microalgae ensures food safety while posing challenges for market entry due to strict Novel Food requirements. Harmonization with global regulations, particularly the Generally Recognized as Safe (GRAS) certification in the United States and the Food Standards Australia New Zealand (FSANZ) rules in Australia, remains a key factor for international trade. The evolving regulatory landscape aims to balance consumer protection with innovation in the growing market for microalgae-based food products.

4. Microalgae as functional ingredients in food formulations

The growing demand for sustainable and nutrient-rich foods has led the food industry to explore microalgae as functional ingredients. Their density in macro- and micro-nutrients offers an opportunity for nutritional enhancement, allowing for improved health profiles of foods without significantly altering consumers' dietary habits [77]. Microalgae can be incorporated into formulations either as whole dried biomass or extracts, depending on the intended application and the need to control sensory and functional attributes. Microalgal extracts provide a targeted means of isolating beneficial compounds or bioactive peptides while minimizing undesirable sensory impacts [15]. Conversely, the use of whole biomass provides a rich and balanced composition. Beyond their nutritional value, the structural biopolymers present in microalgae can modulate the rheology of food systems, supporting their use as natural texturizing agents [78]. Despite these functional benefits, the incorporation of microalgae may negatively influence the colour, flavour, and texture of food products, thereby limiting consumer acceptance [14].

Choices, ranging from cultivation conditions to downstream

Table 3
Products from microalgae authorized as Novel Foods included in the Union List, from 2017 up to the latest revision of February 2025. Maximum levels of the total ingredient or its contribution to the maximum intake of docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) are reported.

Microalgal source	EU regulation references	Approved food categories	Maximum permitted levels	Special conditions
<i>Ulkenia</i> sp. oil	Regulation (EU) 2017/2470	Bakery products, cereal bars, non-alcoholic beverages	200 mg/100 g in bakery; 500 mg/100 g in cereal bars; 60 mg/100 mL in beverages (DHA contribution)	Must be labelled as “Oil from the microalgae <i>Ulkenia</i> sp.”
<i>Odontella aurita</i>	Regulation (EU) 2017/2470	Flavoured pasta, fish soups, marine terrines, broth preparations, crackers, frozen breaded fish	0.5–1.5 % total ingredient depending on category	Must be labelled as “ <i>Odontella aurita</i> microalgae”
<i>Schizochytrium</i> sp. oils (various strains)	Regulations (EU) 2019/109, 2019/387, 2020/1559, 2021/670, 2021/1326, 2022/1365, 2024/2049, 2024/2101	Dairy and dairy analogues, bakery products, cereal bars, cooking fats, infant formula, meat/fish analogues, sports foods	80–600 mg/100 g (DHA/EPA contribution, depending on product category)	Must be labelled as “Oil from the microalgae <i>Schizochytrium</i> sp.” (or specific strain where applicable)
<i>Tetraselmis chuii</i> (dried biomass)	Regulation (EU) 2017/2470	Sauces, special salts, condiments	Up to 20 % total ingredient or 250 mg/day DHA intake	Must be labelled as “Dried microalgae <i>Tetraselmis chuii</i> ” or “Dried microalgae <i>T. chuii</i> ”
<i>Euglena gracilis</i> (dried biomass and beta-glucan extract)	Regulations (EU) 2020/1820, 2024/1046	Cereal bars, yogurt, yogurt beverages, fruit/vegetable juices, meal replacement beverages, total diet replacement products	40–670 mg/100 g total ingredient (depending on category)	Must be labelled as “Dried biomass of <i>Euglena gracilis</i> algae” or “Beta-glucan from <i>Euglena gracilis</i> microalgae”

processing and formulation, highlight several technological challenges that must be addressed to fully unlock the potential of microalgae in food applications (Fig. 2). In particular, sensory attributes and nutrient bioaccessibility are deeply influenced by how the biomass is produced, processed, and integrated into food matrices. The following sections explore these challenges and the innovative strategies being developed to overcome them.

Note: PEF: pulsed electric fields; US: ultrasounds; HPH: high pressure homogenization.

4.1. Challenges and technological considerations in food processing

4.1.1. Sensory profile

Despite their potential, incorporating microalgae into food products presents several technological challenges related to food matrix interactions, sensory properties, and processing constraints. The interaction between microalgal macromolecules and food matrices affects texture, stability, and processing behaviour. Specifically, the protein content of microalgae contributes to emulsification, water-holding, and gelation properties, which are critical for food structure and mouthfeel [79]. Studies have demonstrated that incorporating *Dunaliella salina* into pasta formulations increases water absorption capacity, influencing gelatinization and cooking volume [80]. Similarly, the viscoelastic properties of bakery doughs were modified when microalgae were introduced. For instance, Marzec et al. [81] found that adding 1 % *Chlorella vulgaris* powder to a muffin formulation optimized texture and structure by enhancing elasticity and viscosity, indicating its potential for improving baked goods. However, when the microalgae amount exceeds the optimal threshold, an accelerated rate of staling was observed [82] leading to increased firmness and dryness over time,

likely due to changes in moisture retention and starch retrogradation dynamics. Indeed, these findings suggest that, apart from microalgae concentration, it is crucial to understand which type of flour, such as strong or weak flour, best complements the addition of microalgae. The interaction between flour strength and microalgae could significantly influence the final product's texture, moisture retention, and shelf-life, making it an important variable to optimize in product formulation.

One of the primary barriers to consumer acceptance of microalgae-enriched foods are their strong sensory profiles. Many species exhibit intense green or blue-green pigmentation, as well as earthy, grassy, or marine-like flavours, attributed to volatile organic compounds (VOCs) [83]. *Spirulina* tends to have a salty taste, whereas *Chlorella* has a grassy and umami flavour, which can be desirable in savoury applications but challenging for sweet formulations [84]. These sensory characteristics are species-specific and strongly influenced by cultivation parameters such as light exposure, nutrient availability, and growth mode. Open ponds and PBRs, which rely on light to sustain photoautotrophic growth, often result in biomass rich in pigments such as chlorophylls and carotenoids, responsible for the characteristic green colour. These systems also favour the accumulation of photosynthesis-related VOCs, which can significantly hinder the acceptability of the final product [48]. In contrast, certain microalgae capable of heterotrophic growth inhibit the synthesis of these compounds in the absence of light. As a result, fermenters can produce a biomass with a more neutral sensory profile, enhancing its versatility for food applications [49].

In addition to the selection of the cultivation system, various processing strategies have been developed to mitigate unpleasant flavours and odours, including:

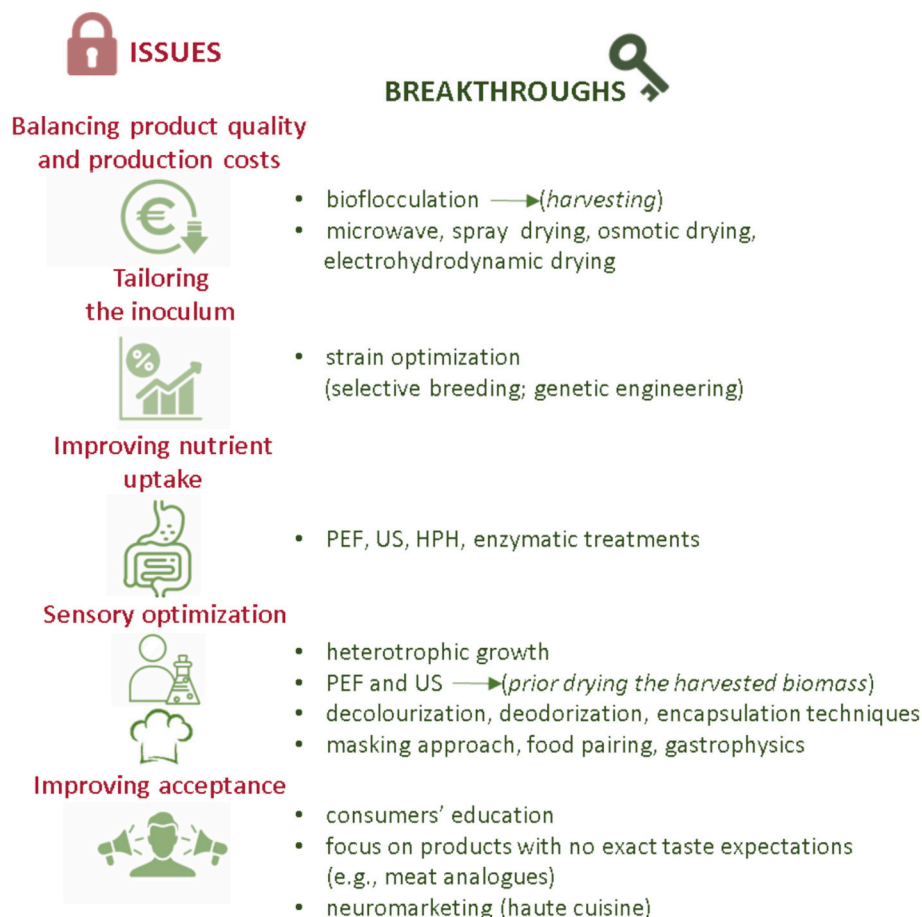


Fig. 2. Key challenges and processing approaches related to the integration of microalgae into food systems.

- encapsulation: coating microalgal components to mask taste and improve stability [5];
- deodorization: removal of undesirable VOCs through controlled processing [83] such as steam distillation, supercritical CO₂ extraction, and solvent extraction or through the addition of deodorant agents [85];
- selective breeding and strain selection: developing species with milder sensory profiles and increased bioactives [6].

Understanding of the chemical composition of microalgae is essential to optimize their use in food applications, as individual compounds are closely linked to specific sensory attributes. Key taste sensations such as umami, sweetness, bitterness, sourness, and saltiness, as well as odour notes like floral, mushroom, seaweed, or fatty, are often driven by defined classes of molecules, including amino acids, nucleotides, organic acids, volatile sulphur compounds, ketones, and aldehydes [86]. Therefore, detailed sensory profiling combined with flavour compound analysis is crucial for guiding targeted formulation, improving palatability, and developing effective flavour enhancement/mitigation strategies.

4.1.2. Nutrients bioaccessibility

Another major challenge in microalgae-based food formulations is maximizing the bioaccessibility of intracellular bioactive compounds, which are often trapped within the microalgal cell walls. While microalgal extracts can enhance bioaccessibility by providing concentrated sources of proteins, antioxidants, and essential fatty acids, their high production costs limit their widespread use, leading food manufacturers to favour whole dried biomass despite its lower digestibility [87]. Among edible microalgae, as already mentioned in Chapter 2, *Spirulina* is naturally highly digestible due to its lack of cellulose, making its proteins and micronutrients readily bioaccessible. In contrast, species such as *Chlorella vulgaris* possess rigid, cellulose-rich cell walls, which act as a barrier to nutrient release, reducing the efficiency of digestion and absorption in the human gastrointestinal tract [88]. *Chlorella* is also known for having a layer of a very resistant polymer called algaenan, which will also hamper the action of enzymes [89]. To overcome these limitations, various cell disruption techniques have been developed to break down the microalgal cell wall structure including:

- pulsed electric field (PEF): a non-thermal technology that applies high-intensity electric pulses (typically between 0.5 and 10 kV/cm) to enhance cell membrane permeability [35]. This method facilitates the release of intracellular compounds while preserving thermolabile nutrients [90]. For example, PEF-induced permeabilization of *Chlorella vulgaris* has been successfully demonstrated by Canelli et al. [91], who observed an approximately threefold increase in lipid bioaccessibility. Similarly, Jaeschke et al. [92] reported improved protein accessibility in *Limnospira platensis* following PEF treatment.
- ultrasonication: a mechanical treatment that utilizes cavitation forces generated by high-frequency acoustic waves (typically between 20 and 40 kHz) to disrupt microalgal cell walls, effectively enhancing nutrient bioaccessibility while preserving functional properties [93]. In a comparative study on *Chlorella vulgaris*, Janczyk et al. [94] demonstrated that ultrasound-treated cells exhibited greater accessibility to gastrointestinal enzymes, thereby increasing protein bioaccessibility. Similarly, do Nascimento et al. [95] and Gille et al. [96] reported enhanced carotenoid bioaccessibility from *Scenedesmus obliquus* and *Phaeodactylum tricornutum*, respectively.
- high pressure homogenization (HPH): a mechanical cell disruption method in which biomass is forced through a narrow valve at high pressure, generating intense mechanical forces, elongational stress, turbulence, and cavitation that lead to cell rupture and particle deformation [97]. While specific bioaccessibility studies are lacking, Safi et al. [17] reported significantly enhanced protein extraction yields following HPH treatment at 2700 bar in *Haematococcus*

pluvialis, *Nannochloropsis oculata*, *Chlorella vulgaris*, and *Limnospira platensis*.

- enzymatic cell lysis: enzyme-assisted hydrolysis selectively degrades cell wall polysaccharides, enhancing the release of bioactive peptides, carotenoids, and polyphenols, while avoiding thermal degradation of sensitive compounds [93]. In *Chlorella vulgaris*, enzymatic treatment has been shown to increase protein bioaccessibility up to 59 % [91]. A detailed understanding of cell wall composition is essential to reduce processing costs and optimize enzymatic efficiency, as it enables the precise selection of enzymes tailored to the structural features of specific microalgal species [98].

While these technologies show promising results in enhancing nutrient bioaccessibility, they also come with economic and scalability challenges. Non-thermal techniques like PEF and ultrasounds are gaining interest for energy-efficient processing, but their commercial application in large-scale food production still requires further optimization and cost reduction strategies. HPH should be further investigated in terms of its impact on the gastrointestinal bioaccessibility of nutrients. Balancing processing efficiency, cost-effectiveness, and nutrient preservation will be key to unlocking the full potential of microalgae as a sustainable and functional food ingredient. Moreover, selecting species based on digestibility potential can optimize formulation strategies for different target markets and nutritional claims.

4.2. Applications of dry microalgae biomass in food categories

Microalgae have been explored in various food categories, particularly in staple products to enhance their nutritional value. Table 4 summarizes key applications, benefits, and challenges associated with microalgae-enriched foods.

In addition to the challenges associated with product reformulation, such as adjusting water content, oil levels, and ensuring a proper balance with binding agents and other ingredients, studies suggest that incorporation levels below 3 % tend to maintain acceptable sensory qualities while minimizing processing-related challenges. In contrast, higher inclusion levels (>5 %) tend to intensify colour and flavour alterations, which can negatively impact consumer acceptance [115]. The future of microalgae in the food industry hinges on overcoming processing and sensory challenges while ensuring cost-effective scalability. The development of mild-tasting, colour-neutral microalgae powders through genetic engineering, combined with innovations in encapsulation techniques, could increase consumer acceptance and broaden applications [90]. Furthermore, regulatory frameworks will play a crucial role in determining permissible inclusion levels and consequent labelling requirements [14].

4.2.1. Microalgae for meat analogues

Microalgae represent a transformative ingredient in the development of next-generation meat analogues.

Several species of microalgae have been explored for their application in this field, each offering distinctive nutritional, technological, and sensory properties. Among the most studied are *Limnospira* sp., known for its balanced essential amino acid profile along with powerful antioxidant activity [58,145,146], *Chlorella vulgaris* and *Chlorella sorokiniana* due to their rich micronutrient content (including vitamins B12 and D) and bioactive pigments that can enhance both nutritional quality and product appearance [58,145], *Haematococcus pluvialis*, which gained attention for its potential to impart a red colour that closely mimics raw meat, thus improving the visual appeal of plant-based products [147]. Other species such as *Auxenochlorella protothecoides* have been evaluated for their performance under high-moisture extrusion conditions [148], while *Tetraselmis* sp., *Euglena gracilis*, and *Nannochloropsis* sp. are gaining traction due to their functional protein content and techno-functional traits [58,149].

The integration of microalgae into meat analogues offers several

Table 4

Applications of dried microalgae biomass in staple foods: benefits and challenges.

Food category	Microalgae used	Benefits	Challenges	References
Pasta	<i>Chlorella</i> , <i>Dunaliella</i> , Spirulina	Increased protein, carotenoids, minerals (e.g., Ca, Fe, Mg, K)	Colour changes, altered taste, texture modifications; higher protein content can increase firmness but may reduce elasticity; microalgal powders compete for water, altering gelatinization and cooking time	[[99]; [80]; [100]]
Bakery products (bread, muffins, biscuits, crackers)	<i>Chlorella</i> , Spirulina	Improved polyphenols content; textural enhancement at ~1 % concentration	Limited protein increase, risk of off-flavours and dough stickiness at high doses; too brittle or crumbly formulations at 5 % concentration; lower loaf volume with microalgae concentrations higher than 3 %	[[101]; [102]]
Gluten-free products	<i>Chlorella</i> , Spirulina	Enhanced protein structure and binding properties (mimicking gluten properties)	Challenging sensory acceptability	[103]
Snacks and chocolate	<i>Chlorella</i> , Spirulina	Increased amino acids and mineral content; higher levels of vitamin B ₁₂ ; enhanced candy-like flavour with 2.5 % Spirulina addition	Risk of taste alterations if incorporation levels are not optimized; variation in chewing characteristics depending on species and strain selection	[[104]; [5]]
Dairy alternatives	<i>Chlorella</i> , <i>Diacronema vlkianum</i> , <i>lutheri</i> , <i>Pavlova Tetraselmis</i> , Spirulina	Decreased syneresis in yogurt; improved ice cream melting time and replacement of artificial dyes with stable natural pigments; enhanced antioxidant capacity in cheese due to high phenolic and carotenoid content	Alteration of sensory properties, including taste and texture; increased viscosity attributed to higher proteins content	[[105]; [106]]
Sauces	<i>Chlorella vulgaris</i> , <i>Dunaliella salina</i> , Spirulina	Reduced acidity and elevated pH decreased sourness and improved palatability (4 % Spirulina); higher apparent viscosity and consistency	Need for spice blending to mask microalgae flavour notes; colour optimisation required through microalgal concentration adjustment	[[107]; [108]]
Beverages and soups	<i>Chlorella vulgaris</i> , Spirulina, <i>Tetraselmis</i> sp.	Enhanced overall nutritional profile and antioxidant activity; 1.5 % microalgae addition positively impacted on the viability of probiotic bacteria in fermented products; increased amount of bioaccessible polyphenols	Texture deterioration (graininess and roughness) observed at high incorporation levels (>5 %); deterioration of sensory attributes at high concentrations (>0.5 % in soups)	[[109]; [110]; [111]]
Meat products (beef patties, pork meatballs, chicken rotti)	<i>Chlorella</i> , Spirulina	Improved emulsion stability and reduced cooking losses at 1 % concentration; increased levels of total phenolics concentration; greater concentrations of EAA	Significant change in the colour parameters	[[112]; [113]; [114]]

advantages. Nutritionally, microalgae often exceed terrestrial crops in protein content, with many species averaging above 50 % dry weight [58,145]. The amino acid composition of these proteins is highly favourable; in some cases, the essential amino acids indices of *Chlorella* and *Limnospira* exceed those of conventional sources such as casein or soy [145].

In terms of functional properties, microalgal proteins exhibit promising traits such as excellent solubility across a wide pH range, high emulsifying capacity, gelling potential, and foam formation ability [58,145]. For example, *Chlorella protothecoides* has demonstrated protein solubility exceeding 84 % from pH 2 to 12, a property superior to soy glycinin which precipitates under acidic conditions [145]. Additionally, the emulsification capacity of microalgal proteins such as those from *C. vulgaris* and *Tetraselmis* sp. are comparable or superior to that of commercial emulsifiers [145]. These functional characteristics are critical in replicating the fibrous, juicy, and fatty textural qualities of animal-based meat.

Despite these advantages, the application of microalgae in meat analogues is not without limitations. One of the key technological challenges is achieving proper texturization during high-moisture extrusion. In the case of *Auxenochlorella protothecoides*, increasing its concentration above 10 % in formulations was found to impair fibrous structure formation [148]. This is attributed to several factors: reduced protein molecular weight, higher solubility, lower hydrophobic side-chain content, and an electrolyte environment that inhibits disulphide bond formation [148]. Such molecular properties hinder protein-protein interactions necessary for building the desired meat-like network. Similar trends have been reported with Spirulina flour. High incorporation levels (30–50 %) in meat analogues resulted in a marked reduction in cutting force [116], indicating diminished structural integrity. FTIR spectroscopy corroborated this observation, revealing a decrease in β -sheet content and an increase in α -helix and β -turn structures with higher Spirulina content [116]. As β -sheets contribute to mechanical strength through extensive hydrogen bonding [117], their reduction leads to softer textures. Conversely, α -helices and β -turns facilitate

enzymatic accessibility by exposing peptide bonds, thereby enhancing protein digestibility [118]. This structural transition illustrates the trade-off between improved nutritional functionality and diminished mechanical performance in microalgae-based meat analogues.

Another challenge lies in sensory acceptance. For instance, high inclusion levels of *Haematococcus pluvialis* in extruded products altered the flavour profile and texture negatively, while low to moderate concentrations (1–5 %) were found optimal for achieving a red meat-like appearance without undesirable aroma [147]. Likewise, yellow-pigmented *Chlorella* has been successfully used to enhance chewiness and colour while reducing off-flavours compared to Spirulina [146]. Optimizing the concentration of microalgae in formulations is critical; inclusion levels below 10 % are generally considered effective in balancing nutritional benefits and minimizing sensory issues [58]. In addition, combining microalgal proteins with modified starches has shown promise. Modified starches enhance the rheological properties of 3D-printable microalgae-based inks, improving texture, viscosity, and yield stress, while also acting as masking agents to reduce off-colours and flavours associated with microalgal biomass [149].

5. Consumers acceptability

The successful market adoption of microalgae-based food products depends on multiple factors influencing consumer perception, willingness to try, and purchasing behaviour. While microalgae have been traditionally consumed in regions like Asia and Central America, they are still perceived as novel in Western markets, where their use remains limited to niche and health-conscious consumer segments. Understanding the barriers and drivers of consumer acceptability is essential for expanding their market reach.

5.1. Factors influencing consumer attitudes toward microalgae

A key barrier to consumer adoption of microalgae-based foods is food neophobia, the reluctance to try unfamiliar foods [119]. Studies indicate

that consumers with lower neophobia levels are more open to incorporating microalgae-based products into their diets [120,121]. Since marketability relies on nutritional benefits and environmental advantages, limited awareness of these aspects can hinder purchasing decisions. A study conducted by Lafarga et al. [122] showed that Spanish consumers' perceptions of microalgae improved significantly after receiving information about their health and sustainability benefits, suggesting that education campaigns and strategic marketing could mitigate food neophobia and increase consumer willingness to try these products. Incorporating microalgae into familiar foods (e.g., pasta, baked goods) further reduces hesitation by minimizing the novelty factor.

Dietary preferences, especially meat consumption habits, also influence the acceptance of microalgae as a food ingredient. Studies indicate that consumers concerned with environmental sustainability, including vegetarians, vegans, and flexitarians, are more likely to adopt plant-based innovations such as microalgae-based foods [123,124]. While vegetarians and vegans represent 5 % and 3 % of European consumers, respectively, flexitarians account for nearly 30 % [125], making them a crucial target group for expanding microalgae-based food consumption. Despite the complementary benefits of microalgae as a nutrient-dense alternative protein source, strong culinary traditions and habitual meat consumption may still act as cultural and habitual barriers, particularly in regions where meat holds a strong symbolic and dietary role.

The sensory profile of microalgae-added food, including taste, colour, and texture, plays a significant role in consumer acceptance. As discussed in Chapter 4.1, microalgae have earthy, marine-like flavours and intense green or blue-green pigmentation, which can be unfamiliar or undesirable in certain food applications [84]. In addition to technological innovations, two principal formulation strategies have emerged to enhance the sensory acceptance of microalgae in food products [126]. The first is the masking approach, which seeks to suppress the intense, often musty or marine notes typical of certain microalgae species by enhancing the dominance of more palatable ingredients. Ingredients with strong citrus, herbal, or umami profiles, such as basil, garlic, or smoked paprika, can obscure undesirable notes without requiring chemical modification [127,128]. The second strategy is known as the flavour-flavour approach, which is grounded in the concept that foods sharing similar volatile compound profiles are more likely to be perceived as harmonious when combined. This method draws directly from the scientific principles underlying food pairing, a broader gastronomic concept that not only considers chemical compatibility but also incorporates textural contrast, nutritional synergy, and cultural significance [129].

Pricing is a crucial determinant of microalgae-based food adoption. Despite belonging to the functional food category, where higher prices are common, cost remains a substantial barrier. Achieving competitive pricing will depend on scalability, production efficiency, and processing cost reductions. A study by Fantechi et al. [120] revealed that 40 % of Italian consumers responded positively to Spirulina-enriched pasta and were willing to pay €1.28 more per kg than for standard pasta. However, higher prices may limit adoption beyond health-conscious and sustainability-aware consumers. Emphasizing nutritional benefits in a clear labelling could justify premium pricing, as consumers tend to pay more for products associated with well-documented health benefits [130].

5.1.1. Strategies to improve consumer acceptance

To increase market penetration and expand consumer acceptance, producers should implement targeted strategies that address both perceptual [131] and economic barriers [121]. Educational campaigns that highlight the nutritional value and environmental advantages of microalgae represent one of the most effective strategies to boost consumer acceptance, particularly among segments with low food neophobia, who are more inclined to embrace such novel foods [123].

Studies have shown that prior familiarity with microalgae is positively associated with consumer liking [127]. However, many consumers remain unfamiliar with the opportunities offered by microalgae as a food ingredient, and clear, science-based communication can play a crucial role in shaping more positive perceptions, particularly among younger generations [126]. Additionally, the gradual incorporation of microalgae into familiar food products, such as pasta, baked goods, soups, and snacks, can help reduce the novelty factor, making these ingredients more approachable especially when their sensory attributes align with consumer expectations since visual coherence play a key role in shaping attitudes [111]. This strategy allows producers to promote their adoption without necessitating significant dietary changes.

As affordability remains a key determinant of consumer choice, optimizing production efficiency and processing costs could enable competitive pricing, making these products more accessible to a broader audience. In this context, microalgae have the potential to supply up to 10 % of global dietary protein demand by 2050, provided that adequate investments are made in production technologies, cost reduction, and consumer acceptance [132].

6. Market considerations and future development

Globally, the microalgae food and beverage market was valued at USD 673.7 million in 2024 and is projected to reach USD 1.42 billion by 2032, with a CAGR of 9.8 % (Credece Research, 2025). The broader algae market, covering various applications, was estimated at EUR 18.5 billion in 2021 and is expected to reach EUR 33.7 billion by 2028 [16]. Despite growing interest, Europe remains a minor player, producing only 0.8 % of macroalgae and 0.63 % of microalgae in 2019, contributing a small fraction of the 56,456 tons of global microalgae production that year. However, the European algae sector is steadily expanding, driven by demand in aquaculture, nutraceuticals, and food production. In 2016–2017, algae-related businesses in the EU generated EUR 161.4 million, with EUR 31.6 million attributed to microalgae, primarily Spirulina (EUR 20.4 million) [56]. France leads European microalgae production, particularly for Spirulina, with 129 companies, followed by Italy (22) and Spain (18). Spain, Germany, France, and Italy are key hubs for microalgae production and processing.

As alternative protein (AP) sources gain traction, microalgae-based foods are benefiting from increasing economic and technological investments. The AP sector, which includes plant-based proteins, cultured meat, and single-cell proteins like microalgae, is projected to grow from USD 108.1 billion in 2025 to USD 589.9 billion by 2035, with Europe as a leading player [133]. In light of this strong investment landscape, microalgae-based foods could follow a similar upward trajectory. Notably, if strategically integrated into the meat analogue sector, microalgae could play a significant role in a rapidly expanding global market which was valued at USD 7.24 billion in 2024 and is projected to grow to USD 16.13 billion by 2032, nearly doubling in less than a decade [134].

6.1. Future perspectives for microalgae in the food industry

Future advancements in technology, product innovation, and market integration strategies will shape microalgae's role in the food industry. Key areas of development include:

- regulatory adaptations and market integration: expanding Novel Food authorizations under EU Regulation 2015/2283 and streamlining regulatory pathways will facilitate broader market entry for microalgae-based foods:

- partnerships with leading food companies: establishing partnerships with major players in the food industry will be essential to increase both the visibility and market penetration of microalgae-based products within mainstream markets. Several business-to-business (B2B) collaborations have already been launched to provide financial support for the industrial scale-up of microalgae production. These initiatives have

facilitated the development of a range of consumer products, such as plant-based dairy alternatives and functional snacks, enriched with microalgal ingredients, thereby accelerating their acceptance and integration into conventional food channels [135];

- technological advancements: enhancing cultivation, harvesting efficiency, and biomass processing will be critical for lowering production costs and improving scalability. Innovations such as strain optimization and energy-efficient drying techniques are expected to improve cost-effectiveness. Genetic engineering is also emerging as a powerful tool to increase strain productivity, boost protein content, and reduce undesirable sensory attributes such as off-flavours and odours, thus broadening the applicability of microalgae in food formulations.

In parallel, non-thermal technologies such as PEF and US processing have demonstrated strong potential for improving sensory quality in food applications. For example, Bi et al. [136] showed that PEF treatment applied to beer inhibited enzymatic activity and reduced the formation of off-flavour compounds during storage, preserving a more favourable organoleptic profile. Likewise, Khandpur and Gogate [137] reported that ultrasound processing maintained the colour, aroma, taste, and overall acceptability of orange juice more effectively than conventional heat treatments. These improvements were largely attributed to the inactivation of degradative enzymes and reduced oxidation, two mechanisms highly relevant for microalgae-based foods. Applying these insights to microalgal biomass, both PEF and ultrasounds could be strategically used immediately after harvesting, when enzymatic activity is highest, to inactivate endogenous lipolytic enzymes [138] and limit the oxidative breakdown of sensitive compounds. In the case of ultrasounds, their degassing effect may also help remove dissolved oxygen, further preventing the formation of volatile sulphur compounds and aroma-deteriorating metabolites. These interventions could stabilize pigments, reduce off-flavour development, and preserve key sensory attributes before drying or extraction. Overall, both technologies emerge as promising pre-treatment options to enhance the flavour quality and consumer acceptance of food-grade microalgal ingredients;

- product innovation and diversification: beyond supplements, microalgae are being integrated into staple foods, meat and dairy alternatives, and functional beverages. Emerging technologies, such as PEF, US, HPH, and enzymatic treatments, are being explored to enhance nutrient absorption. In this context, valorising microalgal proteins and other key compounds in formulations can improve nutritional value, support bioaccessibility, and help overcome sensory barriers in plant-based products, although these benefits often come with increased processing costs;

- microalgae application as a functional protein source in structured meat analogues represents a novel and forward-looking shift. Future developments should prioritize the optimization of high-moisture extrusion processes tailored to the unique physicochemical properties of microalgal proteins, as current methods remain insufficient to consistently achieve the fibrous textures required for meat analogue applications;

- consumer acceptance and sensory optimization: improving sensory appeal (through decolourization and deodorization techniques or via encapsulation, flavour masking techniques, and food pairing), ease of integration into daily diets, and clear nutritional communication will be essential. Targeted marketing and educational campaigns will further drive consumer interest.

6.2. Integrating gastrophysics and food pairing for future microalgae-based foods

As the integration of microalgae into mainstream food systems gains momentum, future directions must embrace more holistic and interdisciplinary approaches, not only to mitigate undesirable traits, but to transform microalgae into valued contributors to gastronomic creativity. In this context, emerging disciplines such as gastrophysics and food pairing science offer promising conceptual and practical

frameworks.

For instance, Coleman et al. [139] demonstrated that species like *Tetraselmis chui* and *Rhodomonas salina* possess seafood-like aromatic profiles, rich in dimethyl sulphide, trimethylamine, and umami-enhancing amino acids, that make them ideal for pairing with plant-based seafood analogues. Supporting this scientific framework, Chua et al. [140] identified high concentrations of umami-active compounds in *Chlorella vulgaris* and *Limnospira platensis*, suggesting culinary pairings with tomatoes, mushrooms, and aged cheeses or vegan fish sauces. These combinations not only enhance taste but also reflect an emerging gastrophysical rationale, a term introduced by Mouritsen [129], which aims to design multisensory food experiences through a systematic understanding of volatile release, texture, and cultural context. Culinary case studies further illustrate this integration. For example, Grahl et al. [127] found that spirulina-enriched pasta flavoured with lemon and basil achieved the highest consumer acceptability among variants, due to successful masking of musty-earthly notes while also creating an appealing flavour contrast, effectively applying both strategies at once. In haute cuisine, these scientific insights are materializing through the emerging field of phycogastronomy. Some pioneering chefs have incorporated *Tetraselmis chui* and *Nannochloropsis gaditana* into dishes where their marine, herbal, and saline notes are elevated via strategic pairings with extra virgin olive oil, citrus emulsions, and dry white wines [141]. These practices do not merely hide the algal notes, they celebrate them, reframing microalgae as gourmet ingredients capable of delivering identity-rich, oceanic complexity. Within this context, neuromarketing insights enrich the gastrophysical approach, by elucidating how multisensory stimuli (such as colour, aroma, texture, and narrative) shape consumer perception and emotional engagement with chef-designed food experiences [142].

By aligning microalgae with the scientific principles of flavour compatibility and the artistic practices of modern gastronomy, researchers and chefs alike are establishing a more sustainable, palatable, and culturally resonant path forward, one that increasingly reflects advanced gastronomic frameworks embracing complexity, cultural meaning, and sensory innovation: a true synthesis of science and culinary art.

7. Conclusions

Owing to their nutrient density, microalgae represent a valuable resource for future food systems, aligning with sustainability goals and consumers' demand for health-promoting, eco-friendly products. The economic scalability of microalgae-based systems depends heavily on improvements in cultivation efficiency and cost-effective downstream processing. Closed cultivation systems offer superior environmental control, product consistency, and higher biomass concentrations, though their broader deployment is hindered by high energy demands, infrastructure costs, and scalability challenges. Innovations in low-energy harvesting and processing, optimized culture media, along with the valorisation of industrial CO₂ emissions as a low-cost, sustainable carbon feedstock, will be crucial for expanding microalgae's role in the sustainable food industry.

Furthermore, cultivation conditions, particularly the use of photoautotrophic or heterotrophic systems, significantly influence the sensory profile of the resulting biomass. Considering these upstream choices in early product development can help improve flavour neutrality, reduce pigmentation intensity, and ultimately enhance consumer acceptability. Additionally, the use of non-thermal post-harvest treatments, such as PEF and ultrasounds, should be explored to mitigate enzymatic and oxidative degradation and stabilize the sensory quality of microalgal biomass prior to drying, the most critical step influencing flavour, colour, texture, and nutrient preservation.

Ultimately, improving the digestibility and bioaccessibility of microalgal biomass requires a species-specific approach, grounded in a thorough understanding of cell wall architecture and composition.

Tailoring processing strategies to the unique structural traits of each microalga is crucial for enhancing nutrient release while maintaining efficiency and cost-effectiveness.

Among the most promising applications, meat analogues stand out, as their novelty leaves room to explore and adapt flavour profiles without clashing with established expectations. In this context, microalgae can be incorporated at concentrations of up to 10 %, a higher threshold than in staple products, allowing for meaningful nutritional contributions while maintaining acceptable sensory characteristics.

Beyond production and processing, enhancing consumer acceptance and refining sensory optimization strategies are key to positioning microalgae-based foods as viable options for mainstream adoption. As haute cuisine increasingly embraces microalgae as premium ingredients, it simultaneously serves as a powerful vehicle for public engagement, leveraging neuromarketing strategies to reshape consumer perceptions and enhance acceptance. By showcasing their gastronomic potential in refined culinary contexts, chefs contribute not only to taste innovation but also to the normalization and desirability of microalgae in broader food culture.

Although Europe currently accounts for a relatively small share of the global algae market, increasing government support, private investments, and technological advancements are driving broader adoption and market expansion. Overcoming regulatory and sensory barriers, alongside supportive policy frameworks and consumer education, will be crucial in transitioning microalgae from a niche application to a widely accepted, nutrient-dense alternative to conventional protein sources, ultimately contributing to a more resilient and sustainable food system.

CRedit authorship contribution statement

Francesca Giroto: Writing – review & editing, Writing – original draft, Supervision, Investigation, Conceptualization. **Alessandro Scapini:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization.

Declaration of competing interest

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

Acknowledgements

Project funded under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3 - Call for tender No. 341 of 15 March 2022 of Italian Ministry of University and Research funded by the European Union – NextGenerationEU; Project code PE00000003, Concession Decree No. 1550 of 11 October 2022 adopted by the Italian Ministry of University and Research, CUP D93C22000890001, Project title “ON Foods - Research and innovation network on food and nutrition Sustainability, Safety and Security – Working ON Foods”.

Data availability

Data will be made available on request.

References

- [1] C. Mbow, C. Rosenzweig, Food security, in: IPCC (Ed.), Climate Change and Land: Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, Cambridge University Press, 2022, pp. 437–550. ISBN 978-1-009-15798-8.
- [2] J. Ranganathan, R. Waite, T. Searchinger, C. Hanson, How to sustainably feed 10 billion people by 2050, in 21 charts, Retrieved from: World Resources Institute, 2018. <https://www.wri.org/insights/how-sustainably-feed-10-billion-people-2050-21-charts>.
- [3] V. Krishnan, Y. Uemura, N.T. Thanh, N.A. Khalid, N. Osman, N. Mansor, Three types of marine microalgae and *Nannochloropsis oculata* cultivation for potential source of biomass production, J. Phys. Conf. Ser. 622 (2015) 012034.
- [4] L. Manu, J.F. Moklensang, W.B. Gunawan, A. Setyawardani, N. Salindeho, R. A. Syahputra, M. Iqhrammullah, F. Nurkolis, Photobioreactors are beneficial for mass cultivation of microalgae in terms of areal efficiency, climate implications, and metabolites content, J. Agric. Food Res. 18 (2024) 101282.
- [5] A. Çelekli, B. Özbal, H. Bozkurt, Challenges in functional food products with the incorporation of some microalgae, Foods 13 (2024) 725.
- [6] T.C. Adarme-Vega, D.K. Lim, M. Timmins, F. Vernen, Y. Li, P.M. Schenk, Microalgal biofactories: a promising approach towards sustainable omega-3 fatty acid production, Microb. Cell Factories 11 (2012) 1–10.
- [7] W. Chen, T. Li, S. Du, H. Chen, Q. Wang, Microalgal polyunsaturated fatty acids: hotspots and production techniques, Front. Bioeng. Biotechnol. 11 (2023) 1146881.
- [8] M. Neves, A. Ferreira, M. Antunes, J. Laranjeira Silva, S. Mendes, M.M. Gil, C. Tecelão, *Nannochloropsis oceanica* as a sustainable source of n-3 polyunsaturated fatty acids for enrichment of hen eggs, Appl. Sci. 11 (18) (2021) 8747.
- [9] O.G. Mouritsen, P. Rhatigan, J.L. Pérez-Lloréns, World cuisine of seaweeds: science meets gastronomy, Int. J. Gastron. Food Sci. 1 (4) (2018) 55–65.
- [10] R. Raja, S. Hemaiswarya, N.A. Kumar, S. Sridhar, R. Rengasamy, A perspective on the biotechnological potential of microalgae, Crit. Rev. Microbiol. 34 (2) (2008) 77–88.
- [11] E. Mathieu-Rivet, N. Mati-Baouche, M.L. Walet-Balieu, P. Lerouge, M. Bardor, N- and O-glycosylation pathways in the microalgae polyphyletic group, Front. Plant Sci. 11 (2020) 609993.
- [12] E.S.J. Thoré, K. Muylaert, M.G. Bertram, T. Brodin, Microalgae, Curr. Biol. 33 (2023) R91–R95.
- [13] E.C., European Commission, Novel Food Catalogue, Retrieved from: https://food.ec.europa.eu/safety/novel-food/novel-food-catalogue_en, 2025.
- [14] V. Verdelho, Algae for food, Retrieved from: Maritime Forum, 2024. https://maritime-forum.ec.europa.eu/contents/algae-food_en.
- [15] M. Caporgno, A. Mathys, Trends in microalgae incorporation into innovative food products with potential health benefits, Front. Nutr. 5 (2018) 58.
- [16] A. Kuech, M. Breuer, I. Popescu, Research for PECH Committee – The Future of the EU Algae Sector, European Parliament, Policy Department for Structural and Cohesion Policies, Brussels, 2023.
- [17] C. Safi, A.V. Ursu, C. Laroche, B. Zebib, O. Merah, P.Y. Pontalier, C. Vaca-Garcia, Aqueous extraction of proteins from microalgae: effect of different cell disruption methods, Algal Res. 3 (2014) 61–65.
- [18] K. Khoo, S.Y. Lee, C.W. Ooi, X. Fu, X. Miao, T.C. Ling, P.L. Show, Recent advances in biorefinery of astaxanthin from *Haematococcus pluvialis*, Bioresour. Technol. 288 (2019) 121606.
- [19] M. Mularczyk, I. Michalak, K. Marycz, Astaxanthin and other nutrients from *Haematococcus pluvialis* – multifunctional applications, Mar. Drugs 18 (9) (2020) 459–479.
- [20] G.D. Scoglio, H.O. Jackson, S. Purton, The commercial potential of *Aphanizomenon flos-aquae*, a nitrogen-fixing edible cyanobacterium, J. Appl. Phycol. 36 (2024) 1593–1617.
- [21] F.A. Ansari, H. Hassan, K.M. Gani, I. Rawat, S.K. Gupta, F. Bux, Influence of nitrogen sources on growth and biochemical composition of *Chlorella sorokiniana*, Biomass Bioenergy 197 (2025) 107832.
- [22] E.W. Becker, Micro-algae as a source of protein, Biotechnol. Adv. 25 (2007) 207–210.
- [23] A.B. Diprat, T. Menegol, J.F. Boelter, A. Zmozinski, M.G. Rodrigues Vale, E. Rodrigues, R. Rech, Chemical composition of microalgae *Heterochlorella luteoviridis* and *Dunaliella tertiolecta* with emphasis on carotenoids, J. Sci. Food Agric. 97 (2017) 3463–3468.
- [24] G.M. Figueroa-Torres, E. Bermejo Padilla, J.K. Pittman, T. Constantinos, Microalgae strain catalogue, 2016.
- [25] K. Wang, X. Wen, Y. Ding, Y. Geng, Y. Yu, W. Tian, Z. Wang, Revealing mechanisms of high protein accumulation in *Graesiella emersonii* WBG-1 under heterotrophic condition, Bioresour. Technol. 418 (2025) 131992.
- [26] W.M. Qazi, S. Ballance, K. Kousoulaki, A.K. Uhlen, D.M. Kleinegris, K. Skjånes, A. Rieder, Protein enrichment of wheat bread with microalgae: *Microchloropsis gaditana*, *Tetraselmis chui* and *Chlorella vulgaris*, Foods 10 (2021) 3078.
- [27] M. Guevara, B.O. Arredondo-Vega, Y. Palacios, K. Saéz, P.I. Gómez, Comparison of growth and biochemical parameters of two strains of *Rhodomonas salina* (Cryptophyceae) cultivated under different combinations of irradiance, temperature, and nutrients, J. Appl. Phycol. 28 (2016) 2651–2660.
- [28] E.T. Chua, P.M. Schenk, A biorefinery for *Nannochloropsis*: induction, harvesting, and extraction of EPA-rich oil and high-value protein, Bioresour. Technol. 244 (2017) 1416–1424.
- [29] K.B. Hadley, J. Bauer, N.W. Milgram, The oil-rich alga *Schizochytrium* sp. as a dietary source of docosahexaenoic acid improves shape discrimination learning associated with visual processing in a canine model of senescence, Prostaglandins Leukot. Essent. Fat. Acids 118 (2017) 10–18.
- [30] B. Quilodrán, I. Hinzpeter, E. Hormazabal, A. Quiroz, C. Shene, Docosahexaenoic acid (C22:6n–3, DHA) and astaxanthin production by *Thraustochytridae* sp. AS4-A1, a native strain with high similarity to *Ulkenia* sp.: evaluation of liquid residues from food industry as nutrient sources, Enzym. Microb. Technol. 47 (2010) 24–30.
- [31] S. Mobin, F. Alam, Some promising microalgal species for commercial applications: a review, Energy Procedia 110 (2017) 510–517.

- [32] J.D. Cruz, V. Vasconcelos, Legal aspects of microalgae in the European food sector, *Foods* 13 (2023) 124.
- [33] M.P. Rai, S. Vasistha, *Microalgae Biotechnology for Wastewater Treatment, Resource Recovery and Biofuels*, Springer, Switzerland, 2023. ISBN 978-3-031-31673-9.
- [34] A. Richmond, Q. Hu, *Handbook of Microalgal Culture: Applied Phycology and Biotechnology*, Wiley Blackwell, 2013 (ISBN 978-0-470-67389-8).
- [35] L. Machado, G. Carvalho, R.N. Pereira, Effects of innovative processing methods on microalgae cell wall: prospects towards digestibility of protein-rich biomass, *Biomass* 2 (2022) 80–102.
- [36] J.B. Moreira, B.S. Vaz, B.B. Cardias, C.G. Cruz, A.C.A. Almeida, J.A.V. Costa, M. G. Morais, Microalgae polysaccharides: an alternative source for food production and sustainable agriculture, *Polysaccharides* 3 (2022) 441–457.
- [37] A.P.F. De Oliveira, A.P.A. Bragotto, Microalgae-based products: food and public health, *Future Foods* 6 (2022) 100157.
- [38] P.L. Show, Global market and economic analysis of microalgae technology: status and perspectives, *Bioresour. Technol.* 357 (2022) 127329.
- [39] F. Giroto, A. Schievano, A. Idà, G.R. Clerici, G. Sala, A. Goglio, L. Piazza, Earthenware-based biofilter configuration for *Spirulina* cultivation on nutrients recycled from food-industry waste streams: a preliminary study, *Bioresour. Technol. Rep.* 18 (2022) 101097.
- [40] S. Villaró, M. Franco, M. García-Vaquero, L. Morán, F. Alarcón-López, T. Lafarga, Composition of microalgae produced using different types of water and nutrient sources, *Algal Res.* 78 (2024) 103394.
- [41] T. Xie, Y. Xia, Y. Zeng, X. Li, Y. Zhang, Nitrate concentration-shift cultivation to enhance protein content of heterotrophic microalga *Chlorella vulgaris*: over-compensation strategy, *Bioresour. Technol.* 233 (2017) 247–255.
- [42] E.G. De Morais, I.L. Nunes, J.I. Druzian, M.G. De Morais, A.P.C. da Rosa, J.A. V. Costa, Increasing the cell productivity of mixotrophic growth of *Spirulina* sp. LEB 18 with crude glycerol, *Biomass Convers. Biorefinery* 14 (2024) 7305–7313.
- [43] J. Alussant, F. Guihéneuf, D.B. Stengel, Impact of temperature on fatty acid composition and nutritional value in eight species of microalgae, *Appl. Microbiol. Biotechnol.* 102 (2018) 5279–5297.
- [44] M.P. Hernando, I.R. Schloss, F.G. de la Rosa, M. De Troch, Fatty acids in microalgae and cyanobacteria in a changing world: contrasting temperate and cold environments, *Biocell* 46 (3) (2021) 607–621.
- [45] T. Grivalský, K. Ranglová, J.A. da Câmara Manoel, G.E. Lakatos, R. Lhotský, J. Masojídek, Development of thin-layer cascades for microalgae cultivation: milestones, *Folia Microbiol.* 64 (2019) 603–614.
- [46] J. Hoffman, R.C. Pate, T. Drennen, J.C. Quinn, Techno-economic assessment of open microalgae production systems, *Algal Res.* 23 (2017) 51–57.
- [47] L. Novoveská, S.L. Nielsen, O.T. Eroldoğan, B.Z. Haznedaroglu, B. Rinkevich, S. Fazi, H. Einarsson, Overview and challenges of large-scale cultivation of photosynthetic microalgae and cyanobacteria, *Mar. Drugs* 21 (2023) 445.
- [48] M. Bürck, A.C. Lemes, M.B. Egea, A.R.C. Braga, Exploring the potential and challenges of fermentation in creating foods: a spotlight on microalgae, *Fermentation* 10 (2024) 649.
- [49] P. Pramanik, Could microalgae fermentation create the superfoods of the future?, Retrieved from: *News-Medical*, 2024. <https://www.news-medical.net/news/20241218/Could-microalgae-fermentation-create-the-superfoods-of-the-future.aspx>.
- [50] H. Sun, W. Zhao, X. Mao, Y. Li, T. Wu, F. Chen, High-value biomass from microalgae production platforms: strategies and progress based on carbon metabolism and energy conversion, *Biotechnol. Biofuels* 11 (2018) 1–23.
- [51] R. Araujo, C. Peteiro, *Algae as Food and Food Supplements in Europe*, EUR 30779 EN, Publications Office of the European Union, Luxembourg, 2021. ISBN 978-92-76-40548-1.
- [52] T. Xi, D.G. Kim, S.W. Roh, J.S. Choi, Y.E. Choi, Enhancement of astaxanthin production using *Haematococcus pluvialis* with novel LED wavelength shift strategy, *Appl. Microbiol. Biotechnol.* 100 (2016) 6231–6238.
- [53] Y. Zhang, X. Li, Y. Li, S. Liu, Y. Chen, M. Jia, B. Ge, Regulation of different light conditions for efficient biomass production and protein accumulation of *Spirulina platensis*, *J. Oceanol. Limnol.* 42 (2024) 174–186.
- [54] V.C. Guedes, G.M. Palma, A.C.L. Horta, An evaluation of light wavelengths, intensity and control for the production of microalgae in photobioreactors: a review, *Braz. J. Chem. Eng.* 41 (2024) 1077–1090.
- [55] S. Smetana, M. Sandmann, S. Rohn, D. Pleissner, V. Heinz, Autotrophic and heterotrophic microalgae and cyanobacteria cultivation for food and feed: life cycle assessment, *Bioresour. Technol.* 245 (2017) 162–170.
- [56] F.V. Calderon, J.S. Lopez, An Overview of the Algae Industry in Europe: Producers, Production Systems, Species, Biomass Uses, Other Steps in the Value Chain and Socio-Economic Data, Publications Office of the European Union, Luxembourg, 2022.
- [57] S. Khanra, M. Mondal, G. Halder, O.N. Tiwari, K. Gayen, T.K. Bhowmick, Downstream processing of microalgae for pigments, protein and carbohydrate in industrial application: a review, *Food Bioprod. Process.* 110 (2018) 60–84.
- [58] J. Zhu, M. Wakisaka, T. Omura, Z. Yang, Y. Yin, W. Fang, Advances in industrial harvesting techniques for edible microalgae: recent insights into sustainable, efficient methods and future directions, *J. Clean. Prod.* 436 (2024) 140626.
- [59] L. Wimmerova, Z. Keken, O. Šolcová, K. Vávrová, A comparative analysis of environmental impacts of operational phases of three selected microalgal cultivation systems, *Sustainability* 15 (2022) 769.
- [60] C.V. Al Rey, H.L. Ong, A.B. Culaba, J.L. Cuello, Conventional drying methods to algal biomass: their applications and recent advances, *Algal Bioreac.* (2025) 139–148.
- [61] R. Pandiselvam, Y. Tak, E. Olum, O.J. Sujayasree, Y. Tekgöl, G. Çalışkan Koç, M. Kumar, Advanced osmotic dehydration techniques combined with emerging drying methods for sustainable food production: impact on bioactive components, texture, color, and sensory properties of food, *J. Texture Stud.* 53 (6) (2022) 737–762.
- [62] T. Defraeye, A. Martynenko, Electrohydrodynamic drying of multiple food products: evaluating the potential of emitter-collector electrode configurations for upscaling, *J. Food Eng.* 240 (2019) 38–42.
- [63] N. Kazemi, M.G. Parashkoochi, A. Mohammadi, D.M. Zamani, Environmental life cycle assessment and energy-economic analysis in different cultivation of microalgae-based optimization method, *Res. Eng. Des.* 19 (2023) 101240.
- [64] R. Mazac, N. Järviö, H.L. Tuomisto, Environmental and nutritional life cycle assessment of novel foods in meals as transformative food for the future, *Sci. Total Environ.* 876 (2023) 162796.
- [65] D. Zhang, S. An, R. Yao, W. Fu, Y. Han, M. Du, J. Wang, Life cycle assessment of auto-tropically cultivated economic microalgae for final products such as food, total fatty acids, and bio-oil, *Front. Mar. Sci.* 9 (2022) 990635.
- [66] S. Schade, T. Meier, Distinct microalgae species for food—part I: a methodological (top-down) approach for the life cycle assessment of microalgae cultivation in tubular photobioreactors, *J. Appl. Phycol.* 32 (2020) 2977–2995.
- [67] F. Giroto, V.O. Biasi, A. Mirto, L. Piazza, Challenges for greening *Spirulina* value chain in terms of freshwater input—a case study, *Chem. Eng. Trans.* 87 (2021) 355–360.
- [68] R. Porcelli, F. Dotto, L. Pezzolesi, D. Marazza, N. Greggio, S. Righi, Comparative life cycle assessment of microalgae cultivation for non-energy purposes using different carbon dioxide sources, *Sci. Total Environ.* 721 (2020) 137714.
- [69] S.S. Ende, A. Noke, Heterotrophic microalgae production on food waste and by-products, *J. Appl. Phycol.* 31 (2019) 1565–1571.
- [70] S. Rossi, D. Carecci, L. Proietti, K. Parati, E. Ficarra, Enhancing the environmental and economic sustainability of heterotrophic microalgae cultivation: kinetic modelling and screening of alternative carbon sources, *Chem. Eng. J. Adv.* 19 (2024) 100632.
- [71] J. Ruiz, R. Wijffels, M. Dominguez, M.J. Barbosa, Heterotrophic vs autotrophic production of microalgae: bringing some light into the everlasting cost controversy, *Algal Res.* 64 (2022) 102698.
- [72] F. Marques, F. Pereira, L. Machado, J.T. Martins, R.N. Pereira, M.M. Costa, P. Geada, Comparison of different pretreatment processes envisaging the potential use of food waste as microalgae substrate, *Foods* 13 (2024) 1018.
- [73] C. Kurrer, Z. Wala, in: *European Parliament (Ed.), Sicurezza alimentare. Note tematiche sull'Unione Europea*, 2024. Retrieved from: <https://www.europarl.europa.eu/factsheets/it/sheet/51/sicurezza-alimentare>.
- [74] G. Markou, I. Chentir, I. Tzovenis, Microalgae and cyanobacteria as food: legislative and safety aspects, in: *Cultured Microalgae for the Food Industry*, Academic Press, 2021, pp. 249–264. ISBN 978-0-128-21080-2.
- [75] T.F. Prüsser, P.G. Braun, C. Wiacek, Microalgae as a novel food: potential and legal framework, *Ernährungs-Umschau* 68 (2021) 78–85.
- [76] G.C. Zittelli, S. Magini, C. Unamunzaga, V. Verdelho, J. Paulcadoret, Algae as a novel food in Europe, Retrieved from: *European Algae Biomass Association*, 2021. <https://www.eaba-association.org/en/resources>.
- [77] M.T. Baker, P. Lu, J.A. Parrella, H.R. Leggett, Consumer acceptance toward functional foods: a scoping review, *Int. J. Environ. Res. Public Health* 19 (2022) 1217.
- [78] T.M. Bernaerts, L. Gheysen, I. Foubert, M.E. Hendrickx, A.M. Van Loey, The potential of microalgae and their biopolymers as structuring ingredients in food: a review, *Biotechnol. Adv.* 37 (8) (2019) 107419.
- [79] R.C. Vieira, J.A. Medeiros, M.A.A. Nascimento, A.K.S. Abud, A. Raymundo, C.E. F. Silva, Microalgae as sustainable food: incorporation as strategy in the formulation of functional food, in: *New and Future Developments in Microbial Biotechnology and Bioengineering*, Elsevier, 2020, pp. 19–30 (ISBN 978-0-128-20528-0).
- [80] F. El-Baz, S. Abdo, A. Hussien, Microalgae *Dunaliella salina* for use as food supplement to improve pasta quality, *Int. J. Pharm. Sci. Rev. Res.* (2022) 45–51.
- [81] A. Marzec, P. Kramarczuk, H. Kowalska, J. Kowalska, Effect of type of flour and microalgae (*Chlorella vulgaris*) on the rheological, microstructural, textural, and sensory properties of vegan muffins, *Appl. Sci.* 13 (2023) 7632.
- [82] C.A. Wang, H. Onyeaka, T. Miri, F. Soltani, *Chlorella vulgaris* as a food substitute: applications and benefits in the food industry, *J. Food Sci.* 89 (2024) 8231–8247.
- [83] A.K. Gohara-Beirigo, M.C. Matsudo, E.A. Cezare-Gomes, J.C.M. Carvalho, E.D. G. Danesi, Microalgae trends toward functional staple food incorporation: sustainable alternative for human health improvement, *Trends Food Sci. Technol.* 125 (2022) 185–199.
- [84] J. Ampofo, L. Abbey, Microalgae: bioactive composition, health benefits, safety and prospects as potential high-value ingredients for the functional food industry, *Foods* 11 (2022) 1744.
- [85] B.S.O. Colonia, G.V. de Melo Pereira, J.C. de Carvalho, S.G. Karp, C. Rodrigues, V. T. Soccol, C.R. Soccol, Deodorization of algae biomass to overcome off-flavors and odor issues for developing new food products: innovations, trends, and applications, *Food Chem. Adv.* 2 (2023) 100270.
- [86] Y. Zhao, M. Bai, D. Qiu, J. Zhang, N. Zhao, G. Feng, A.O. Obadina, Comparative evaluation of sensory and instrumental flavor profiles of four edible microalgae: *Spirulina platensis*, *Chlorella pyrenoidosa*, *Chlamydomonas reinhardtii*, and *Haematococcus pluvialis*, *Algal Res.* 82 (2024) 103628.
- [87] C. Chen, T. Tang, Q. Shi, Z. Zhou, J. Fan, The potential and challenge of microalgae as promising future food sources, *Trends Food Sci. Technol.* 126 (2022) 99–112.

- [88] H. Jia, F. Ren, H. Liu, Evaluation of bioaccessibility and bioavailability of dietary bioactives and their application in food systems, *Food Biosci.* 62 (2024) 105428.
- [89] D.S. Domozych, M. Ciancia, J.U. Fangel, M.D. Mikkelsen, P. Ulvskov, W. G. Willats, The cell walls of green algae: a journey through evolution and diversity, *Front. Plant Sci.* 3 (2012) 82.
- [90] P.A. Diankristanti, N.H.E. Ho, J.H. Chen, D. Nagarajan, C.Y. Chen, Y.M. Hsieh, I. S. Ng, J.S. Chang, Unlocking the potential of microalgae as sustainable bioresources from up to downstream processing: a critical review, *Chem. Eng. J.* 488 (2024) 151124.
- [91] G. Canelli, I. Kuster, L. Jaquenod, L. Buchmann, P.M. Martínez, Z. Rohfritsch, A. Mathys, Pulsed electric field treatment enhances lipid bioaccessibility while preserving oxidative stability in *Chlorella vulgaris*, *Innov. Food Sci. Emerg. Technol.* 75 (2022) 102897.
- [92] D.P. Jaeschke, G.D. Mercali, L.D.F. Marczak, G. Müller, W. Frey, C. Gusbeth, Extraction of valuable compounds from *Arthrospira platensis* using pulsed electric field treatment, *Bioresour. Technol.* 283 (2019) 207–212.
- [93] M. Demarco, J.O. de Moraes, Á.P. Matos, R.B. Derner, F. de Farias Neves, G. Tribuzi, Digestibility, bioaccessibility and bioactivity of compounds from algae, *Trends Food Sci. Technol.* 121 (2022) 114–128.
- [94] P. Janczyk, C. Wolf, W.B. Souffrant, Evaluation of nutritional value and safety of the green microalgae *Chlorella vulgaris* treated with novel processing methods, *Arch. Zootech.* 8 (2005) 132–147.
- [95] T.C. do Nascimento, P.N. Pinheiro, A.S. Fernandes, D.C. Murador, B.V. Neves, C. R. de Menezes, L.Q. Zepka, Bioaccessibility and intestinal uptake of carotenoids from microalgae *Scenedesmus obliquus*, *LWT* 140 (2021) 110780.
- [96] A. Gille, R. Hollenbach, A. Trautmann, C. Posten, K. Briviba, Effect of sonication on bioaccessibility and cellular uptake of carotenoids from preparations of photoautotrophic *Phaeodactylum tricornutum*, *Food Res. Int.* 118 (2019) 40–48.
- [97] J. Magpusao, I. Oey, B. Kebede, Evaluation of the bioprotective potential of gastrointestinal digest fractions of *Arthrospira* sp. and *Nannochloropsis* sp. suspensions treated with high pressure homogenisation, *Sustainable Food Technology* 2 (2024) 222–231.
- [98] P.H. Baudelet, G. Ricochon, M. Linder, L. Muniglia, A new insight into cell walls of *Chlorophyta*, *Algal Res.* 25 (2017) 333–371.
- [99] M. Fradique, A.P. Batista, M.C. Nunes, L. Gouveia, N.M. Bandarra, A. Raymundo, Incorporation of *Chlorella vulgaris* and *Spirulina maxima* biomass in pasta products. Part 1: preparation and evaluation, *J. Sci. Food Agric.* 90 (2010) 1656–1664.
- [100] I. Hernández-López, M. Abadias, V. Prieto-Santiago, Á. Chic-Blanco, J. Ortiz-Solà, I. Aguiló-Aguayo, Exploring the nutritional potential of microalgae in the formulation of bakery products, *Foods* 13 (2024) 84.
- [101] S. Sukhikh, S. Ivanova, V. Dolganyuk, I. Pilevinova, A. Prosekov, E. Ulrikh, S. Noskova, P. Michaud, O. Babich, Evaluation of the prospects for the use of microalgae in functional bread production, *Appl. Sci.* 12 (2022) 12563.
- [102] A. Raymundo, P. Fradinho, M.C. Nunes, Application of microalgae in baked goods and pasta, in: *Handbook of Food and Feed from Microalgae*, Academic Press, 2023, pp. 317–334 (ISBN 978-0-323-99196-4).
- [103] A. Ferreira, I. Guerra, M. Costa, J. Silva, L. Gouveia, Future perspectives of microalgae in the food industry, in: T. Lafarga, G. Acien (Eds.), *Cultured Microalgae for the Food Industry*, Academic Press, 2021, pp. 387–433 (ISBN 978-0-12-821080-2).
- [104] F. Fanari, J. Comaposada, F. Boukid, E. Climent, A.C. Coma, L. Guerrero, M. Castellari, Enhancing energy bars with microalgae: a study on nutritional, physicochemical and sensory properties, *J. Funct. Foods* 109 (2023) 105768.
- [105] H. Hernández, M.C. Nunes, C. Prista, A. Raymundo, Innovative and healthier dairy products through the addition of microalgae: a review, *Foods* 11 (2022) 755.
- [106] D. Iriani, B. Hasan, T. Warningsih, H. Putra, R. Simatupang, Z. Zahtamal, H. Anami, Formulation and evaluation of a probiotic drink fortified chlorella for enhanced health benefits, *BIO Web Conf.* 136 (2024).
- [107] L. Almeida, L. Cruz, B. Machado, I. Nunes, J.A. Costa, E. Ferreira, P. Lemos, J. Druzian, C. Oliveira de Souza, Effect of the addition of *Spirulina* sp. biomass on the development and characterization of functional food, *Algal Res.* 58 (2021) 102387.
- [108] Z. Uribe-Wandurraga, M. Igual, P. García-Segovia, J. Martínez-Monzó, Physicochemical and rheological characterisation of microalgae-enriched ketchups and their sensory acceptability, *Int. J. Gastron. Food Sci.* 26 (2021) 100424.
- [109] I.M.A. Ibrahim, E.G. El-Dreny, Preparation of functional drinks using spirulina algae, *Acta Sci. Pol. Technol. Aliment.* 113 (2022) 50–62.
- [110] N.I. Csantos, E. Simon, B.E. Teleky, K. Szabo, Z.M. Diaconeasa, D.C. Vodnar, N. C. Ciont, O.L. Pop, Development of a fermented beverage with *Chlorella vulgaris* powder on soybean-based fermented beverage, *Biomolecules* 13 (2023) 245.
- [111] T. Lafarga, F.G. Acien-Fernández, M. Castellari, S. Villaró, G. Bobo, I. Aguiló-Aguayo, Effect of microalgae incorporation on the physicochemical, nutritional, and sensorial properties of an innovative broccoli soup, *LWT* 111 (2019) 167–174.
- [112] M. Momchilova, D. Gradinarska-Ivanova, D. Yordanov, G. Zsivanovits, N. Pats, Effect of different protein sources (plant, cricket powder and microalgae) on the technological and functional properties and sensory characteristics of pork meatballs, *Meat Technol.* 65 (2024) 25–35.
- [113] O. Parniakov, S. Toepfl, F.J. Barba, D. Granato, S. Zamuz, F. Galvez, J.M. Lorenzo, Impact of the soy protein replacement by legumes and algae-based proteins on the quality of chicken rotti, *J. Food Sci. Technol.* 55 (7) (2018) 2552–2559.
- [114] T. Žugčić, R. Abdelkebir, F.J. Barba, A. Rezek-Jambrak, F. Gálvez, S. Zamuz, D. Granato, J.M. Lorenzo, Effects of pulses and microalgal proteins on quality traits of beef patties, *J. Food Sci. Technol.* 55 (2018) 4544–4553.
- [115] F. Boukid, M. Castellari, Food and beverages containing algae and derived ingredients launched in the market from 2015 to 2019: a front-of-pack labeling perspective with a special focus on Spain, *Foods* 10 (2021) 173.
- [116] M. Palanisamy, S. Toepfl, R. Berger, C. Hertel, Physico-chemical and nutritional properties of meat analogues based on *Spirulina*/lupin protein mixtures, *Eur. Food Res. Technol.* 245 (2019) 1889–1898.
- [117] N. Cohen, C.D. Eisenbach, Molecular mechanics of beta-sheets, *ACS Biomater. Sci. Eng.* 6 (4) (2020) 1940–1949.
- [118] F. Ashkar, J. Wu, Effects of food factors and processing on protein digestibility and gut microbiota, *J. Agric. Food Chem.* 71 (23) (2023) 8685–8698.
- [119] S.A. Siddiqui, O. Zannou, I. Karim, Awad Kasmia, N.M.H. J. Golaszewski, V. Heinz, S. Smetana, Avoiding food neophobia and increasing consumer acceptance of new food trends—a decade of research, *Sustainability* 14 (2022) 10391.
- [120] T. Fantechi, C. Contini, L. Casini, Pasta goes green: consumer preferences for spirulina-enriched pasta in Italy, *Algal Res.* 75 (2023) 103275.
- [121] R. Weinrich, O. Elshiewy, A cross-country analysis of how food-related lifestyles impact consumers' attitudes towards microalgae consumption, *Algal Res.* 70 (2023) 102999.
- [122] T. Lafarga, R. Rodríguez-Bermúdez, A. Morillas-España, S. Villaró, M. García-Vaquero, L. Moran, A. Sanchez Zurano, C. González-López, F. Acien-Fernández, Consumer knowledge and attitudes towards microalgae as food: the case of Spain, *Algal Res.* 54 (2021) 102174.
- [123] B.F. Lucas, T.A. Brunner, Attitudes and perceptions towards microalgae as an alternative food: a consumer segmentation in Switzerland, *Algal Res.* 78 (2024) 103386.
- [124] R. Weinrich, O. Elshiewy, Preference and willingness to pay for meat substitutes based on micro-algae, *Appetite* 142 (2019) 104353.
- [125] F.J. Perez-Cueto, L. Rini, I. Faber, M.A. Rasmussen, K.B. Bechtold, J. J. Schouteten, H. De Stur, How barriers towards plant-based food consumption differ according to dietary lifestyle: findings from a consumer survey in 10 EU countries, *Int. J. Gastron. Food Sci.* 29 (2022) 100587.
- [126] M. Olsen, K. Olsen, P. Jensen, Consumer acceptance of microalgae as a novel food – where are we now? And how to get further, *Physiol. Plant.* 176 (2024) e14337.
- [127] S. Grahl, M. Strack, A. Mensching, D. Mörlin, Alternative protein sources in Western diets: food product development and consumer acceptance of spirulina-filled pasta, *Food Qual. Prefer.* 84 (2020) 103933.
- [128] M.C. Nunes, J. Ferreira, A. Raymundo, Volatile fingerprint impact on the sensory properties of microalgae and development of mitigation strategies, *Curr. Opin. Food Sci.* 51 (2023) 101040.
- [129] O. Mouritsen, Gasitrophysics of the oral cavity, *Curr. Pharm. Des.* 22 (15) (2016) 2195–2203.
- [130] M. Alsubhi, M. Blake, T. Nguyen, I. Majmudar, M. Moodie, J. Ananthapavan, Consumer willingness to pay for healthier food products: a systematic review, *Obes. Rev.* 24 (2022) e13525.
- [131] S. Villaró, I. Viñas, T. Lafarga, Consumer acceptance and attitudes toward microalgae and microalgal-derived products as food, in: *Cultured microalgae for the food industry*, Academic Press, 2021, ISBN 978-0-128-21080-2, pp. 367–385.
- [132] E. Stephens, L. Wagner, L.L. Ross, B. Hankamer, Microalgal production systems: global impact of industry scale-up, in: *Microalgal Biotechnology: Integration and Economy*, De Gruyter, Berlin/Boston, 2012, pp. 267–306 (ISBN 978-3-110-29832-1).
- [133] Future Market Insights, Alternative protein market insights - sustainable food trends 2025 to 2035 (2025). Retrieved from: <https://www.futuremarketinsights.com/reports/alternative-protein-market>.
- [134] Fortune Business Insights, Meat Substitutes Market Size, Share & COVID-19 Impact Analysis, By Source (Soy, Wheat, Pea, and Others), By Type (Tofu, Tempeh, Seitan, Quorn, and Others), By Distribution Channel (Supermarkets/Hypermarkets, Convenience Stores, Online Retail, and Others), and Regional Forecast, 2024–2032, Retrieved from: <https://www.fortunebusinessinsights.com/industry-reports/meat-substitutes-market-100239>, 2024.
- [135] N. Bradley, Harvest, Protein Production Technology International, Retrieved from: <https://mydigitalpublication.co.uk/publication/?i=842287&p=78&pp=1&view=issueViewer>, 2025. ISSN 2753-6424.
- [136] X. Bi, F. Liu, L. Rao, J. Li, B. Liu, X. Liao, J. Wu, Effects of electric field strength and pulse rise time on physicochemical and sensory properties of apple juice by pulsed electric field, *Innov. Food Sci. Emerg. Technol.* 17 (2013) 85–92.
- [137] P. Khandpur, P.R. Gogate, Understanding the effect of novel approaches based on ultrasound on sensory profile of orange juice, *Ultrason. Sonochem.* 27 (2015) 87–95.
- [138] F. Hubert, L. Poisson, C. Loiseau, L. Gauvry, G. Pencreac'h, J. Hérault, F. Ergan, Lipids and lipolytic enzymes of the microalga *Isochrysis galbana*, *OCL Oilseeds Fats Crops Lipids* 24 (2017) D407.
- [139] B. Coleman, C. Van Poucke, B. Dewitte, A. Ruttens, T. Moerdijk-Poortvliet, C. Latsos, J. Robbens, Potential of microalgae as flavoring agents for plant-based seafood alternatives, *Future Foods* 5 (2022) 100139.
- [140] W.C. Chua, A.Y. Yeo, W. Yuan, Y.Y. Lee, L. Ikasari, J. Dharmawan, C. M. Delahunty, Flavour characterization of twelve species of edible algae, *Algal Res.* 80 (2024) 103540.
- [141] J.L. Pérez-Lloréns, Microalgae: from staple foodstuff to avant-garde cuisine, *Int. J. Gastron. Food Sci.* 21 (2020) 100221.
- [142] A. Mengual-Recuerda, V. Tur-Viñes, D. Juárez-Varón, Neuromarketing in haute cuisine gastronomic experiences, *Front. Psychol.* 11 (2020) 1772.

- [143] Z. Yaakob, E. Ali, A. Zainal, M. Mohamad, M.S. Takriff, An overview: biomolecules from microalgae for animal feed and aquaculture, *J. Biol. Res.-Thessaloniki* 21 (1) (2014) 6.
- [144] A. Katsimichas, M. Katsouli, N. Spantidos, M.C. Giannakourou, P. Taoukis, Effect of high-pressure homogenization on the functional and emulsifying properties of proteins recovered from *Auxenochlorella pyrenoidosa*, *Appl. Sci.* 15 (1) (2024) 131.
- [145] Y. Fu, T. Chen, S.H.Y. Chen, B. Liu, P. Sun, H. Sun, F. Chen, The potentials and challenges of using microalgae as an ingredient to produce meat analogues, *Trends Food Sci. Technol.* 112 (2021) 188–200.
- [146] A. Bakhsh, J. Park, K.A. Baritugo, B. Kim, S. Sil Moon, A. Rahman, S. Park, A holistic approach toward development of plant-based meat alternatives through incorporation of novel microalgae-based ingredients, *Front. Nutr.* 10 (2023) 1110613.
- [147] C. Liu, S. Cheng, H. Wang, M. Tan, Pickering emulsion stabilized by *Haematococcus pluvialis* protein particles and its application in dumpling stuffing, *Food Res. Int.* 170 (2023) 112957.
- [148] C. Sägesser, J.M. Kallfelz, S. Boulos, J. Dumpler, L. Böcker, T. Mair, A. Mathys, Structurability of microalgae, soy and pea protein for extruded high-moisture meat analogues, *Food Hydrocoll.* 156 (2024) 110290.
- [149] A. Mirzapour-Kouhdasht, P. Biparva, D.J. McClements, F. Garavand, M. Garcia-Vaquero, Formulation of inks for 3D printing of microalgae-based meat analogues and the role of modified starch: a review, *Int. J. Food Sci. Technol.* 59 (11) (2024) 8618–8629.