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*Review*

# Microalgae-Based Functional Foods: A Blue-Green Revolution in Sustainable Nutrition and Health

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**Abstract:** The projected global population of 9.22 billion by 2075 necessitates sustainable food sources that provide health benefits beyond essential nutrition, as the relationship between food biochemistry and human well-being is becoming increasingly significant. Microalgae are simple microscopic organisms rich in various bioactive compounds, such as pigments, vitamins, polyunsaturated fatty acids, polysaccharides, bioactive peptides, and polyphenols, which can be used to develop novel foods with potential health benefits. Bioactive substances offer numerous health benefits, including anti-inflammatory, anticancer, antioxidant, anti-obesity, and heart-protective effects. However, incorporating microalgal biomass into functional food products presents several challenges, including species diversity, fluctuations in biomass production, factors affecting cultivation, suboptimal bioprocessing methods, inconclusive evidence regarding bioavailability and safety, and undesirable flavors and aromas in food formulations. Despite these challenges, significant opportunities exist for the future development of microalgae-derived functional food products. Extensive investigations are essential to overcome these challenges and enable the large-scale commercialization of nutritious microalgae-based food products. This review aims to examine the potential of microalgae as natural ingredients in functional food production, explore the factors limiting their industrial acceptance and utilization, and assess the safety issues associated with human consumption.

**Keywords:** bioactive compounds; nutraceuticals; antioxidants; polyunsaturated fatty acids; pigments; human health

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## 1. Introduction

Chronic diseases (e.g., cardiovascular disease, neoplasm, diabetes mellitus, cerebrovascular accident, and Alzheimer's disease) are significant public health concerns that require long-term management. Such chronic conditions are frequently associated with dietary patterns characterized by a relatively high intake of fat, salt, refined carbohydrates, and

cholesterol [1,2]. As the world population ages, there is growing concern regarding the increasing susceptibility of older adults to chronic health conditions, which has become a significant challenge [3]. In addition to an aging population and the increased prevalence of chronic diseases, continuous improvements in both life expectancy and quality of life, as well as significant adverse effects associated with pharmaceutical interventions, necessitate the development of safety-verified foods enriched with essential nutrients [4,5]. The consumption of foods fortified with functional ingredients, such as proteins, vitamins, minerals, fiber, probiotics, and antioxidants, may lower the risk of developing chronic diseases and enhance physical and mental health [6,7].

In recent decades, significant research has focused on functional foods, particularly with respect to improving food health and technology [8]. The increasing prominence of functional foods has led to increased consumer awareness of food quality and the associated health benefits of various food products [1]. Consequently, there has been a significant increase in consumer interest in nutritious foods and the demand for health-promoting food products. This trend has necessitated the development of innovative functional foods to address the emerging demands [1,9]. However, the development of functional foods is not only an intricate and costly process involving uncertainty and risk factors, but the adoption of such foods by consumers is also a multifaceted and gradual process influenced by numerous variables [10]. As consumer uncertainty and skepticism towards innovative functional foods may affect their acceptance of these products, it is essential to understand how consumers respond to functional foods [11].

Microalgae and cyanobacteria have gained global attention and have emerged as potential sources of functional ingredients, including proteins, polyunsaturated fatty acids (PUFAs), polysaccharides, antioxidants, pigments, vitamins, bioactive peptides, polyphenols, and other compounds that are important for human health [12,13]. Microalgae have been consumed as a human food source for millennia, and their incorporation into diets can alleviate stress on resource-intensive agricultural crops [14]. Among the world's most ancient plant forms, microalgae first emerged approximately 3.5 billion years ago. Microalgae are prokaryotic or eukaryotic organisms that thrive through oxygenic photosynthesis and require light, carbon dioxide, water, and nutrients such as phosphorus and nitrogen [15]. Microalgae and cyanobacteria are found in diverse ecosystems, ranging from freshwater and marine habitats to extreme environmental regions, such as arid deserts, polar regions, hot springs, and desert rocks. The adaptation level of microalgae makes them major biomass producers under sustainable conditions, which helps in water recycling and reduces pollution emissions without competing with agriculture [16]. Moreover, they can be transformed into a range of economically valuable products, including biofuels, cosmetics, renewable chemicals, functional foods, additives, colorants, and phytohormones (Figure 1) [12,17,18].

Several microalgae and cyanobacteria have gained regulatory approval for human consumption because of their high nutritional value and potential health benefits. The U.S. Food and Drug Administration (FDA) has recognized *Arthrospira* sp., *Chlorella* sp., *Dunaliella* sp., and *Haematococcus pluvialis* as Generally Recognized as Safe (GRAS), allowing their use in dietary supplements and functional foods [19]. In the European Food Safety Authority (EFSA)'s Novel Food Safety Regulation (EU) No 2015/2283, species such as *Aphanizomenon flos-aquae*, *Arthrospira platensis*, *Chlorella vulgaris*, *Tetraselmis chuii*, and *H. pluvialis* have been approved for human consumption, highlighting their potential importance as sustainable sources of proteins, polyunsaturated fatty acids (PUFAs), and antioxidants [20]. Additionally, *C. vulgaris* and *Chlorella pyrenoidosa* have been widely used in various food applications because of their protein content and immune-boosting properties. These approvals highlight the growing role of microalgae in the functional

food industry, supporting their integration into health-promoting diets and sustainable food production systems. In addition, microalgae and cyanobacteria have gained recognition as sustainable platforms for producing recombinant pharmaceutical proteins and edible vaccines. Researchers have successfully engineered species such as *Chlamydomonas reinhardtii* to produce therapeutic proteins, including monoclonal antibodies, hormones, and enzymes. Additionally, microalgae have been explored for developing oral vaccines against diseases such as hepatitis B and malaria, offering a scalable and potentially more accessible approach to vaccination [21].

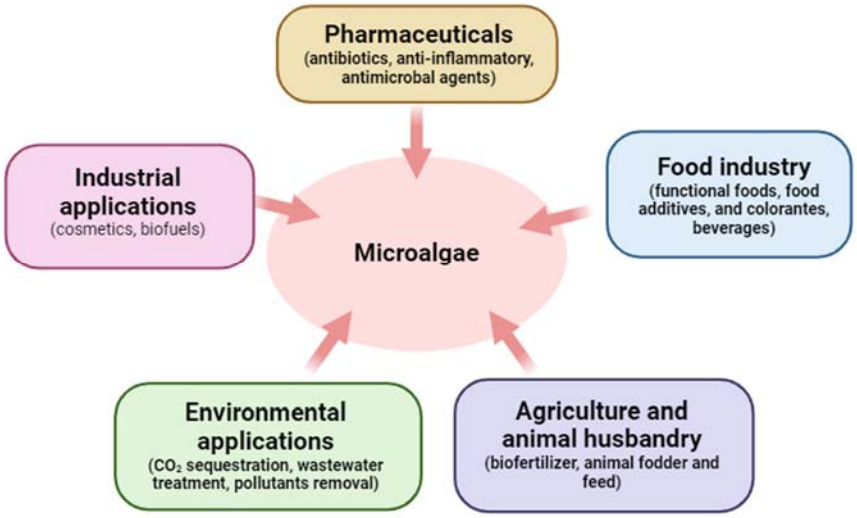



**Figure 1.** Biotechnological applications of microalgae and cyanobacteria in various sectors.

This review presents an innovative approach to developing functional foods using microalgae, highlighting recent research on their promising attributes and potential applications in the food industry. This study examined the biochemical composition, nutritional benefits, and functional properties of microalgal biomass, as well as the technological and sensory characteristics of foods containing microalgae. This study outlines the current trends and future prospects for viable methods of incorporating microalgae into staple foods as a sustainable means of enhancing human health and promoting bioeconomy. This review also addresses environmental concerns and obstacles associated with the implementation of this technology in the near future.

## 2. Challenges in Microalgae Cultivation and Bioprocessing

Microalgae cultivation has immense potential for sustainable biomass production. However, several critical challenges must be addressed to enhance its efficiency and economic feasibility, including species diversity, fluctuations in biomass productivity, factors influencing cultivation, and suboptimal bioprocessing methodologies.

### *2.1. Species Diversity in Microalgae Cultivation*

Microalgae exhibit an extensive range of taxonomic species, with estimates suggesting the existence of over 70,000 species across approximately 64 classes [22]. This extensive diversity presents significant opportunities for biotechnological applications; however, it also introduces complexities in strain selection for cultivation purposes [18,23]. Each species differs significantly in its morphological traits, growth kinetics, biochemical composition, and environmental tolerance, necessitating meticulous selection based on specific production goals [22,24].

The taxonomic diversity of microalgae includes groups such as diatoms (Bacillariophyceae), which alone may comprise approximately 100,000 species, many of which

remain underexplored for biotechnological applications [22]. Advancements in molecular tools and next-generation sequencing have facilitated the identification of cryptic species, thereby expanding the repository of strains available for cultivation [23]. Understanding the physiological and metabolic capabilities of these species is crucial for optimizing their utilization in biofuel production, nutraceuticals, and wastewater treatment [4,25,26].

In cultivation systems, the selection between monocultures and polycultures is influenced by species diversity [24,26]. Monocultures allow for optimized conditions customized to a single species' requirements but are susceptible to environmental stress, contamination, and biological invasions. In contrast, polycultures incorporate multiple species and have shown enhanced ecological resilience, nutrient uptake efficiency, and improved biomass stability [26].

Diverse microalgal communities have been observed to utilize resources more efficiently owing to complementary interactions among species. Such interactions result in higher lipid production, which is a desirable trait for biofuel applications [27]. Co-cultivation of multiple species has also been observed to improve $CO_2$ fixation rates and nutrient recycling efficiency, making it a viable approach for sustainable large-scale microalgal production [23]. Despite these advantages, the implementation of polycultures introduces several operational challenges, such as the management of interspecies competition, maintenance of stable community compositions, and optimization of growth conditions for multiple strains. Additionally, the complexity of harvesting mixed cultures and processing biomass for downstream applications may increase operational costs [23,26]. Although species diversity offers advantages in terms of system stability and productivity, it necessitates careful management and strategic optimization to utilize its full potential in microalgae cultivation systems.

### *2.2. Microalgae Cultivation Under Various Trophic Conditions*

Microalgae exhibit significant metabolic flexibility, allowing them to grow under various trophic conditions, including autotrophic, heterotrophic, photoheterotrophic, and mixotrophic conditions. Understanding these metabolic modes is essential for optimizing microalgal biomass cultivation for applications in biofuel production, wastewater treatment, and other biotechnological processes. Each cultivation mode has its own advantages and limitations, influencing the efficiency and cost-effectiveness of large-scale microalgae production.

Autotrophic cultivation relies on light and $CO_2$ as the primary energy and carbon sources, respectively, with approximately 1.83 kg $CO_2$ required to produce 1 kg of dry biomass. It is estimated that the production of 220 tons $yr^{-1}$ of biomass consumes approximately 366.66 tons $yr^{-1}$ of $CO_2$ annually [28]. Species such as *Arthrospira*, *Chlorella*, *Dunaliella*, *Haematococcus*, and *Nannochloropsis* are widely cultivated on a commercial scale under autotrophic conditions [29], often in photobioreactors that optimize cell growth by providing adequate light energy. Specifically, open raceway ponds are commonly used because of their ease of operation, exposure to natural sunlight, and relatively low operational costs. Commercial photobioreactors are generally classified into two types: (i) circular ponds with rotating arms for agitation and (ii) raceway ponds with paddlewheels to maintain culture circulation. Closed photobioreactors are constructed in flat or tubular forms, configured in manifold or serpentine designs, and positioned horizontally or vertically using transparent materials such as glass or plastic. However, their high infrastructure costs and limitations in light penetration due to shadow effects pose significant challenges to biomass productivity [30].

Heterotopic microalgal species typically depend on photosynthesis for growth and cell development. However, certain species can grow in the absence of light using organic

carbon sources [31]. Such conditions facilitate the use of conventional bioreactors, such as stirred tank systems, which are simple to operate, suitable for large-scale production, and reduce cultivation costs [30]. Heterotrophic cultivation results in higher biomass yields and increased growth rates than autotrophic and mixotrophic cultivation. However, this method is limited to certain native species that require specific enzymatic pathways for carbon metabolism in the absence of light, including *Chlorella* sp., *Neochloris oleoabundans*, *Scenedesmus* sp., and *Thraustochytrium* sp. [32,33]. Another limitation of this method is the reduced synthesis of light-dependent metabolites, particularly pigments.

In photoheterotrophic and mixotrophic cultivation, microalgae utilize organic carbon sources in the presence of light to enable the growth of species that cannot thrive under strictly heterotrophic conditions [31]. Photoheterotrophic cultivation relies on light as an energy source while metabolizing organic compounds without $CO_2$ fixation, similar to heterotrophic growth [34,35]. In contrast, mixotrophic cultivation integrates $CO_2$ fixation and organic carbon assimilation, allowing microalgae to utilize multiple carbon sources simultaneously [36].

Mixotrophic cultivation provides several advantages over autotrophic, photoheterotrophic, and heterotrophic cultivation, including enhanced biomass yields and growth rates [37], as shown in Table 1. The increase in biomass is attributed to improved photosynthetic efficiency, with decreased photoinhibition and lower photooxidative damage [37,38]. Mixotrophic organisms independently regulate photosynthetic and oxidative carbon metabolism, resulting in higher growth rates than other cultivation methods. Furthermore, unlike heterotrophic systems, microalgae under mixotrophic conditions can synthesize light-dependent metabolites similar to those produced in photoautotrophic cultivation, such as pigments and lipids, which play an essential role in photoprotection within photosynthetic membranes [30].

**Table 1.** Comparison of dry biomass production among autotrophic, heterotrophic, and mixotrophic modes of microalgal cultivation.

| Species | Autotropic (g $L^{-1}$) | Heterotrophic (g $L^{-1}$) | Mixotrophic (g $L^{-1}$) | Substrate | Reference |
|---|---|---|---|---|---|
| *Arthrospira platensis* | 0.51 | 0.39 | 0.80 | Glucose | [39] |
| *Botryococcus braunii* | 1.14 | 1.75 | 2.46 | Glucose | [38] |
| *Chlorella* sp. | 0.22 | 0.18 | 0.37 | Glycerol | [40] |
| *Chlorella* sp. | 1.3 | 2.5 | 2.7 | Glucose | [41] |
| *Chlorella* sp. | 0.22 | 0.17 | 0.45 | Sucrose | [36] |
| *Chlorella minutissima* | 0.45 | 1.02 | 0.89 | Glucose | [34] |
| *C. minutissima* | 0.899 | 0.364 | 0.630 | Acetate | [42] |
| | 0.899 | 0.328 | 1.007 | Citrate | |
| | 0.899 | 0.656 | 1.164 | Sucrose | |
| | 0.899 | 0.740 | 2.456 | Glucose | |
| | 0.899 | - | 0.120 | Propionate | |
| *Chlorella protothecoides* | 0.52 | 1.10 | 2.67 | Glycerol | [43] |
| *Chlorella sorokiniana* | 1.70 | 2.78 | 4.57 | Glucose | [44] |
| *Chlorella vulgaris* | 2.47 | 1.52 | 3.91 | Glucose | [37] |
| *C. vulgaris* | 1.08 | 0.40 | 2.62 | Cane molasses | [45] |

**Table 1.** *Cont.*

| Species | Autotropic (g $L^{-1}$) | Heterotrophic (g $L^{-1}$) | Mixotrophic (g $L^{-1}$) | Substrate | Reference |
|---|---|---|---|---|---|
| *Desmodesmus* sp. | 1.83 | 0.58 | 0.79 | Glucose | [46] |
| *Desmodesmus salina* | 0.59 | 0.90 | 1.16 | Glucose | [47] |
| *Isochrysis galbana* | 0.56 | 0.83 | 0.89 | Glucose | |
| *Nannochloropsis oculata* | 0.54 | 1.46 | 1.69 | Glucose | |
| *Scenedesmus obliquus* | 1.1 | 2.2 | 2.3 | Glucose | |
| *Micractinium inermum* | 5.00 | 0.21 | 5.30 | Glucose and acetate | [48] |

### 2.3. Factors Influencing Microalgae Production and Commercial Feasibility

Microalgae production is influenced by several critical factors, including the light intensity, temperature, pH, and nutrient availability. Light is essential for photosynthesis in microalgae, and each species requires an optimal light intensity range for its maximum growth. For example, *Scenedesmus obliquus* grows at 11,100 lx, *C. vulgaris* at 3960 lx, *Dunaliella salina* at 3700 lx, *Nannochloropsis salina* at 18,500 lx, *C. reinhardtii* at 14,800 lx, and *Scenedesmus almeriensis* at 102,250 lx [24]. Temperature is another important factor that influences the metabolic activities and growth rates of microalgae. Most microalgal species exhibit optimal growth at temperatures ranging from 20 to 30 °C. For instance, *C. vulgaris* grows best between 25 and 30 °C, *Nannochloropsis oculate*, *Rhodomonas salina*, and *Isochrysis galbana* achieve maximum biomass production at 14 °C, and *Dixioniella grisea* at 26 °C [49].

The pH of the growth medium significantly affects microalgal growth by influencing nutrient uptake and metabolic processes. Most microalgae prefer a neutral to slightly alkaline pH. For example, *S. obliquus* grows optimally at pH 8, *C. vulgaris* exhibits optimal growth at a neutral pH, and *N. salina* prefers a pH of 8 for optimal growth [24]. Nutrient availability, such as nitrogen, phosphorus, carbon, and trace elements, plays a vital role in the growth of microalgae. The concentrations of these nutrients directly impact growth rates and metabolite production, including lipids. For instance, *C. vulgaris* shows reduced growth when nitrogen and phosphorus concentrations fall below 31.5 mg/L and 10.5 mg/L, respectively. Nitrogen limitation can reduce overall growth but may enhance carbohydrate and lipid production [25]. The economic feasibility of cultivating commercial microalgae species varies. For instance, the production cost of *C. vulgaris* is approximately USD 6.5 $kg^{-1}$ of lipid, while *Tetraselmis suecica* costs around USD 7.0 $kg^{-1}$ of lipid. *Nannochloropsis* sp. has a higher production cost of approximately USD 8.3 $kg^{-1}$ of lipid [50].

### 2.4. Biomass Recovery Methods and Their Challenges

The harvesting of microalgal cells from large volumes of liquid media represents a significant challenge in large-scale production, which accounts for at least 20% of the overall production cost, mainly because of the microscopic size and low density of microalgal cells [51]. Various extraction methods have been established, including gravity sedimentation, centrifugation, filtration, flotation, and flocculation. Centrifugation is a widely used technique for separating microalgal cells from the growth medium using centrifugal force. This method is effective, easy to operate, and supports continuous processing [52]. However, excessive harvesting rates can result in significant energy consumption, and the potential for cell damage due to centrifugal forces can influence the economic viability of microalgae cultivation by centrifugation [53]. Nonetheless, reducing the centrifugal force or processing duration can help mitigate these issues, making centrifugation suitable for small-scale operations [54].

The sedimentation technique utilizes gravitational force by increasing the biomass density to settle microalgal cells. However, the size and density of algal cells constrain the settling rate, causing the process to be inefficient. The gravity sedimentation method is suitable for harvesting larger microalgal cells (>70 μm) [55] and often requires integration with other methods, such as flocculation or centrifugation, to reduce sedimentation time and enhance sedimentation efficiency [56]. The flotation technique separates microalgal cells using microbubbles (<0.1 mm in diameter) to create a foam of algal cells that moves upward toward the surface of the growth medium [52]. Studies have shown that the foam flotation technique can increase the biomass yield by up to 98.4% in *Chlorella* sp. [57]. This technique provides the advantage of relatively quick harvesting and high yields.

Filtration involves separating solids from liquids using a semi-permeable membrane with minute pores that selectively permits the flow of certain particles [55]. Various filtration methods include vacuum, pressure, dead-end, and tangential flow filtration. Tangential flow filtration includes microfiltration, macrofiltration, nanofiltration, ultrafiltration, and reverse osmosis [58]. Membrane-based filtration is the most efficient technique for collecting low-density microalgal biomass, such as that of *Chlorella* sp. [59]. Despite these advantages, membrane fouling and the expense of changing the filter membranes are the most important considerations. The flocculation technique aggregates dispersed charged microalgal cells into concentrated clusters for solid–liquid separation [52]. Methods include physical (electric and magnetic), chemical (inorganic and organic), and biological techniques. Electric flocculation is reliable and energy-efficient; however, it can result in significant biomass contamination by heavy metals [60]. Magnetic flocculation improves biomass separation using magnetic force; however, it is expensive and primarily suitable for small-scale industries or laboratories [61]. Chemical flocculation is a widely accepted method, but it can result in the accumulation of heavy metals in biomass and pose hazardous risks [62]. Biological flocculation is cost-effective, environmentally friendly, and non-toxic, reducing the risk of chemical pollution. However, it is important to evaluate the efficiency of large-scale cultivation [63].

## 3. Bioactive Components of Microalgal Biomass

Microalgae are microscopic photosynthetic organisms that synthesize bioactive molecules and produce biomass from carbon dioxide, light, and nutrients [64]. Owing to their minimal growth requirements, microalgae can sustainably generate highly nutritious molecules, such as carbohydrates, lipids, proteins, and bioactive compounds, including PUFAs, vitamins, pigments, and phycobiliproteins [65,66] (Table 2). The unique properties of microalgae have garnered attention in the food, cosmetics, pharmaceutical, and nutraceutical industries. For instance, they are used in the production of functional foods, skincare products, pharmaceutical drugs, and dietary supplements because of their potential medical, industrial, and biotechnological applications [67].

**Table 2.** Nutritional profile and bioactive compounds of microalgae species used in functional foods.

| Microalgae Species | Proteins (% DW) | Carbohydrates (% DW) | Lipids (% DW) | Vitamins | Minerals | Bioactive Compounds | References |
|---|---|---|---|---|---|---|---|
| *Arthrospira* spp. | 50–70 | 10–20 | 5–10 | B1, B2, B12, E | Fe, Ca, Mg, Zn, P, K | Phycocyanin, C-phycocyanin, flavonoids, phenolic acids, PUFAs (n-3) fatty acids, oleic acid, linolenic acid, palmitoleic acid, β-carotene, lutein, zeaxanthin, tocopherols (vitamin E), neophytadiene, and phytol | [68,69] |
| *Chlorella vulgaris* | 43–61 | 12–26 | 5–58 | $B_1$, $B_2$, $B_3$, provitamin A | Fe, Ca, Mg | Lutein, beta-carotene, polyphenols, phytosterols, and sulphated polysaccharides | [70–72] |
| *Chlamydomonas reinhardtii* | 41.4–46.9 | 21.5–27.8 | 13.2–24.7 | C, provit-amin A | Ca, Mg, P, K, Fe, Se | Beta-carotene, lutein, retinol, chlorophylls a and b, and polysaccharides | [73,74] |
| *Dunaliella salina* | 34–57 | 14–33 | 6–14 | A, B12, C, E | Ca, P, Fe | β-Carotene and astaxanthin | [71,75,76] |
| *Nannochloropsis* sp. | 28.8–40 | 27–37.6 | 18.4–28 | B12, C, E, K | Ca, P, Na, Mg, Zn, Fe | Carotenoids (β-carotene, astaxanthin, canthaxanthin, violaxanthin, and zeaxanthin), polyphenols, and chlorophylls | [77–80] |
| *Haemato-coccus pluvialis* | 29–45 | 15–17 | 20–25 | A, E | Fe, Ca, Mg, P | Astaxanthin, lutein, β-carotene, and tocopherols | [81,82] |
| *Isochrysis galbana* | 27–43.29 | 25.40–34 | 10.95–25.3 | B1, B12, C, E | Fe, Ca, Mg, P | Fucoxanthin and DHA | [82–84] |
| *Tetraselmis* sp. | 13–48 | 6.4–36.2 | 37–60 | A, B1, B2, B6, B12, C, E | Ca, Mg, P, K, Na, S | β-carotene and lutein | [85] |
| *Porphyridium cruentum* | 28–39 | 40–57 | 5–14 | B1, B2, B6, C, E | K, Ca, P, Mg, Fe, Zn, Se | Sulfated polysaccharides, phycoerythrin, phycocyanin, ARA, and EPA | [71,86,87] |
| *Scenedesmus* sp. | 31–56 | 10–48 | 5–15 | B1, B2, C, E | K, P, Mg, Fe, Zn | Carotenoids, antioxidants, and phenolic compounds | [71,75,88,89] |
| *Phaeodac-tylum tri-cornutum* | 29–43.29 | 14.85–40 | 35–45 | B1, B12, C, E | Ca, Fe, Zn | Fucoxanthin, phenolic compounds (4-hydroxybenzaldehyde, ferulic acid, and caffeic acid), and chrysolaminarin | [77,84,90–92] |

Abbreviations: DW: Dry weight; ARA: arachidonic acid; EPA/DHA: eicosapentaenoic acid/docosahexaenoic acid; GLA: gamma-linolenic acid; and PUFAs: polyunsaturated fatty acids.

Bioactive compounds found in microalgae have demonstrated significant health benefits and potential therapeutic applications for chronic and degenerative diseases. Studies have shown that compounds such as polysaccharides, fibers, carotenoids, peptides, and amino acids are associated with positive health effects, such as those related to atherosclerosis [93], cancer [15,94], cardiovascular diseases [95], cholesterol [96], obesity [97], inflammation [94], neurodegenerative diseases [98], type 2 diabetes [99], gut health [100], bone health [101], and antiviral and antioxidant activities [102]. Given the prevalence of chronic diseases, novel treatment and preventive strategies are required to address these issues

in the future. Therefore, microalgae may play a significant role in the development of innovative functional food products [103]. In addition to their nutritional profiles and potential health benefits, microalgae are environmentally significant organisms. They can thrive in diverse ecosystems, proliferate, and even grow under saline conditions, thereby eliminating the need for freshwater conditions, which is a notable advantage over traditional agriculture [18]. Additionally, microalgae can be processed using eco-friendly techniques, such as autohydrolysis. This method involves the breakdown of microalgal cell walls with water under high temperature and high pressure conditions. This approach maximizes the extraction of bioactive compounds and promotes sustainability within the circular economy model [104].

### *3.1. Polysaccharides*

Carbohydrates are essential components of microalgal biomass, and their content varies by genus and species [105]. They are classified as storage and structural carbohydrates, including alginic acid, alginates, carrageenan, agar, laminarans, fucoidans, ulvans, and their derivatives [106]. The production of polysaccharides depends on the type of microalgae; cyanophytes accumulate glycogen and semi-amylopectin, chlorophytes synthesize starch, rhodophytes produce floridean starch, and diatoms generate chrysolaminarin and β-glucan [12]. Polysaccharides exhibit various biological activities, including immunomodulatory, antioxidant [107], and anticancer activities [94]. Polysaccharides from *C. pyrenoidosa* reduce inflammation, motor activity impairment, dopamine expression changes, microglial activation, and peripheral immunomodulatory responses in a mouse model of Parkinson's disease [108].

### *3.2. Fatty Acids*

Microalgae produce an extensive range of fatty acid compounds, such as glycerolipids, sterols, short- and long-chain hydrocarbons, waxes, and pigments, which are essential components of the lipid fraction of microalgal species [109]. Typically, the accumulation of lipid-like compounds in microalgae ranges from 20 to 50% of the dry biomass weight. Fatty acid biosynthesis begins with the conversion of acetyl coenzyme A to malonyl-CoA, which is mediated by acetyl-CoA carboxylase in the triacylglycerol synthesis pathway (Figure 2). Fatty acids are classified as saturated or unsaturated, based on their hydrocarbon chain structure. Saturated fatty acids, such as palmitic and stearic acids, found in animal fats and tropical oils, have single bonds between all carbon atoms, creating straight and rigid structures. In contrast, unsaturated fatty acids (UFAs) contain one or more double bonds in their hydrocarbon chains and are subdivided into monounsaturated (one double bond) and polyunsaturated (two or more double bonds) fatty acids [110]. PUFAs are a subclass of UFAs that include α-linolenic acid (ALA), arachidonic acid (AA), eicosapentaenoic acid (EPA), docosahexaenoic acid (DHA), and γ-linolenic acid (GLA) [111] (Figure 3).

Omega-3 fatty acids belong to a specific group of PUFAs, consisting of ALA, and are found mainly in vegetable oils and nuts, such as English walnuts (9–10%) and hemp seeds (8.8%) [112]. DHA and EPA are derived from PUFAs and are primarily obtained from fish oils. However, studies have shown that certain microorganisms, such as microalgae, also contain high levels of EPA and DHA [113]. This finding highlights the crucial role of microalgae in the production of essential fatty acids in the diet. DHA is vital for brain cell development and requires adequate dietary intake to maintain its levels. Gonzalez-Soto and Mutch [114] found that an ALA-rich diet synthesized and accumulated DHA in the brain 100 times faster than a DHA-rich diet. ALA-rich diets also resulted in nearly three times higher DHA synthesis than that of direct DHA uptake in the brain. Currently, nutritional organizations such as the World Health Organization and the Food and Drug

Administration recommend a daily consumption of DHA ranging from 0.2 to 0.3 g, and 1.4 g of EPA for healthy individuals [112], and between 1.0 and 4.0 g of DHA and EPA per day for individuals with coronary heart disease [115]. Research has shown that a daily intake of ALA exceeding 2.11 g is associated with decreased peripheral neuropathy and a reduced likelihood of sudden coronary artery disease in affected individuals [116].

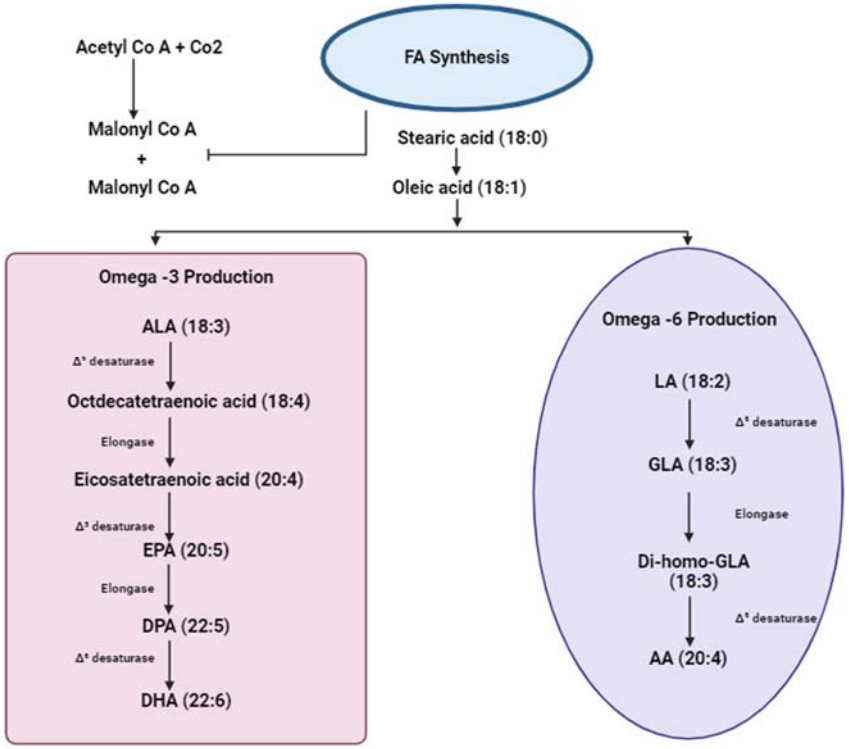



**Figure 2.** Biosynthesis of omega-3 and -6 polyunsaturated fatty acids in microalgae.

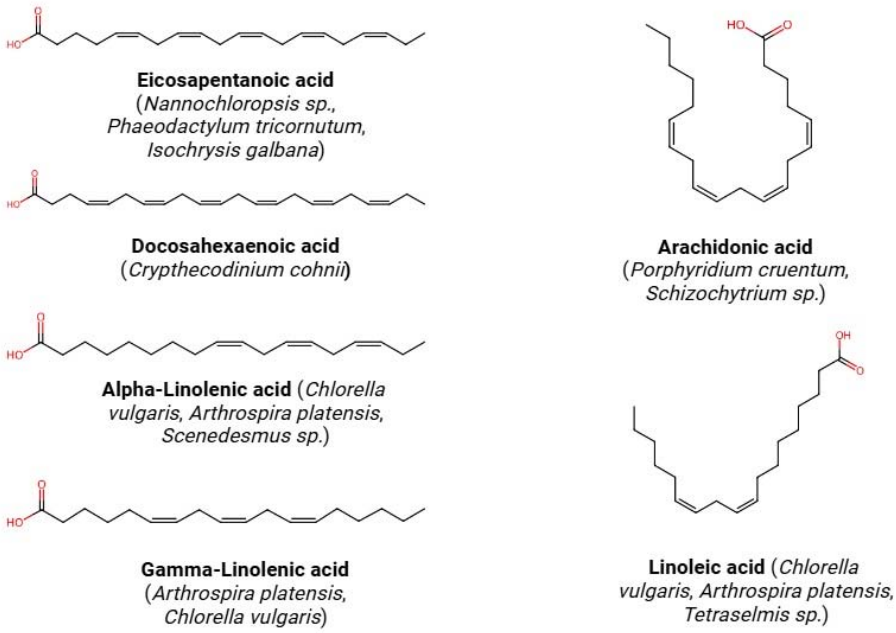



**Figure 3.** The chemical structures of polyunsaturated fatty acids from microalgae and their potential for functional food applications.

Omega-6 fatty acids, including linoleic acid (LA) and AA, are essential for numerous physiological processes in the body, particularly in healthy bones, controlling metabolic

functions, and promoting hair and skin growth [117]. *Porphyridium cruentum* is the only microalga that produces significant quantities of AA, whereas other rhodophytes contain less than 0.2% AA on a dry weight basis [118]. The recommended daily dose for healthy individuals is based on the omega-3 to omega-6 intake ratio, which is typically between 1:1 and 1:4. This ratio is not just a number but a crucial factor that can significantly impact human health. A prolonged deviation in this ratio may cause various health issues, including atherosclerosis, type 2 diabetes, high blood pressure, cerebrovascular accidents, cancer, oxidative stress, elevated triacylglycerol (TAG) levels, cardiovascular diseases, and other chronic diseases. High omega-6 PUFA consumption exacerbates the atherogenic effect of specific genotypes, whereas increased EPA and DHA intakes mitigate this effect. Therefore, maintaining an optimal omega-3 to omega-6 ratio is not just a recommendation but also a necessity for human health [119]. Dietary LA can negatively impact the transformation of ALA into EPA/DHA through competitive inhibition of the Δ5 and Δ6 desaturase enzymes (Figure 2) [114]. The production of EPA and DHA occurs in two phases: the transformation of acetate into oleic acid (OA), followed by the conversion of OA into LA and ALA. Subsequently, desaturation and elongation steps lead to the formation of DHA and EPA, respectively [120]. Certain microalgal classes, including Chlorophyceae, Eustigmatophyceae, Bacillariophyceae, Cryptophyceae, Chrysophyceae, and Prasinophyceae, produce significant amounts of EPA [121]. The microalga *Crypthecodinium cohnii* can accumulate DHA at 25–60% of its overall fatty acid content [122]. In contrast, *Nitzschia laevis* can accumulate 75.9% of its total EPA, which is distributed as 22.6% monoacylglycerides, 37.4% TAGs, and 15.9% phosphatidylcholine [123].

### *3.3. Proteins, Peptides, and Amino Acids*

Microalgae are considered an alternative protein source owing to their high protein content [124]. They provide more protein than traditional sources; for example, *A. platensis* contains 55–70% protein, and *C. vulgaris* includes 42–55% protein per dry matter. Additionally, microalgae provide higher amino acid quality than meat, poultry, and dairy products [14]. Various microalgal protein products have been developed based on cell protein content and purity and are classified as concentrates, hydrolysates, isolates, and bioactive peptides [125]. The main challenge in utilizing microalgae for protein consumption is their cellulose-based cell wall, which cannot be broken down by human digestive enzymes [126]. Efficient cell disruption techniques are required for the extraction of functional proteins from microalgal biomass [127]. These techniques include enzymatic processing [128], microwave application [129], pulsed electric energy combined with ultrasonication [125], pulsed electric field treatment [130], high-pressure homogenization [131], bead milling with enzymatic hydrolysis [105,132], chemical and mechanical approaches [133], and innovative methods such as osmotic shock [134]. The selection of a particular processing method is largely determined by the desired peptide structure [135].

Bioactive peptides obtained from microalgal proteins using various methods have shown significant potential for enhancing health. Enzymatic hydrolysis is considered the most suitable method because it allows for control over the process, preserves the amino acid structure, maintains nutritional value and functionality, and minimizes the use of solvents and toxic chemicals [12]. These peptides, purified using salting-out or solvent extraction methods, can be separated by chromatographic methods, membrane separation, or electromembrane filtration, followed by lyophilization [12]. Microalgal peptides have been found to enhance the cardiovascular health of functional foods [135], and exhibit a range of beneficial activities, including antioxidant, antihypertensive, anticancer, antiatherosclerotic, immunosuppressive, and hepatoprotective activities [136].

Microalgae, which can synthesize all 20 amino acids, are traditional sources of essential amino acids that are vital for human nutrition [137]. In light of current global concerns regarding food security, the identification of sustainable sources of bioactive peptides from essential human food proteins has become increasingly crucial. The development of technologies for the extraction and application of sustainable protein sources is equally important. Microalgae are considered excellent and sustainable protein sources of bioactive peptides [125]. The therapeutic potential of microalgae-derived peptides—particularly under conditions of oxidative stress, high blood pressure, immune disorders, type 2 diabetes, inflammation, and cancer—highlights the importance of these efforts [137].

### *3.4. Pigments and Vitamins*

With the increasing popularity of natural products and the expanding functional food and nutraceutical industries, there is a growing need for natural colorants to substitute synthetic food colorants [138]. Microalgae are considered highly promising organisms because their photosynthetic system synthesizes various pigments, including chlorophyll a, chlorophyll b, chlorophyll c, β-carotene, astaxanthin, xanthophylls, and phycobiliproteins [139] (Figure 4). These pigments provide vibrant colors and various health benefits, reassuring consumers of the safety and advantages of using natural food colorants in their diets. Pigment synthesis may vary among microalgal species and is influenced by temperature, salinity, light intensity, photoperiod, pH, and nutrient availability [140]. For example, β-carotene, an orange pigment produced by *D. salina*, is used in the production of butter, margarine, cheese, and soft drinks. Astaxanthin is a reddish-salmon pigment that was isolated from *H. pluvialis* [12]. Phycobiliproteins extracted from *P. cruentum*, *Synechococcus* spp., and *Arthrospira* spp. can serve as natural colorants for dairy products, candies, chewing gums, and ice cream [17]. Phycocyanin, a blue pigment, is used to improve the appearance of food [141]. Additional pigments include chlorophylls, bixin, canthaxanthin, fucoxanthin, lutein, violaxanthin, zeaxanthin, phycoerythrin, and tocopherol, all of which have unique colors and sources [142]. Pigment extraction entails biomass pretreatment (enzyme lysis, acid/base treatment, and mechanical disruption), solvent or alternative extraction (supercritical fluid, microwave, ultrasound, and enzyme), followed by a purification phase to concentrate, purify, and eliminate contaminants [12]. In addition to their roles as pigments, numerous studies have highlighted the functional and health-related benefits of these compounds (Table 3).

**Table 3.** Potential health benefits of secondary metabolites isolated from specific microalgal species.

| Microalgae | Metabolite | Concentration | Bioactive Effect | References |
|---|---|---|---|---|
| *Scenedesmus obliquus* | Carotenoids | 0.25–2.5 mg·kg$^{-1}$ body weight | Antioxidant activity, reduction in lipid peroxidation | [96] |
| *Haematococcus pluvialis* | Astaxanthin | 1.95–2.75% | Antibacterial, anticancer, anti-inflammatory, antioxidative, neuroprotective, antimicrobial | [143] |
| *Arthrospira platensis* | Phycocyanin | 100–500 µL ml$^{-1}$ | Anti-inflammation, antidiabetic, anticancer | [144] |

**Table 3.** *Cont.*

| Microalgae | Metabolite | Concentration | Bioactive Effect | References |
|---|---|---|---|---|
| *Heterochlorella luteoviridis* | Zeaxanthin | 0.244 mg $g^{-1}$ | Improved eye health, antidiabetic | [145] |
| *Odontella* sp. | Fucoxanthin | 5.13 mg $g^{-1}$ | Antioxidative, anticancer, anti-cholesterol, antidiabetic, antitumor | [146] |
| *A. platensis* | Phycocyanin | 5 µM | Reduction in fat accumulation in the liver caused by nonalcoholic fatty liver disease | [147] |
| *Dunaliella salina* | β-carotene | 0.01–15.0 g $L^{-1}$ | Anticancer, antioxidative, antihypertensive, neuroprotective, protection against macular degeneration, anti-cholesterol | [148] |

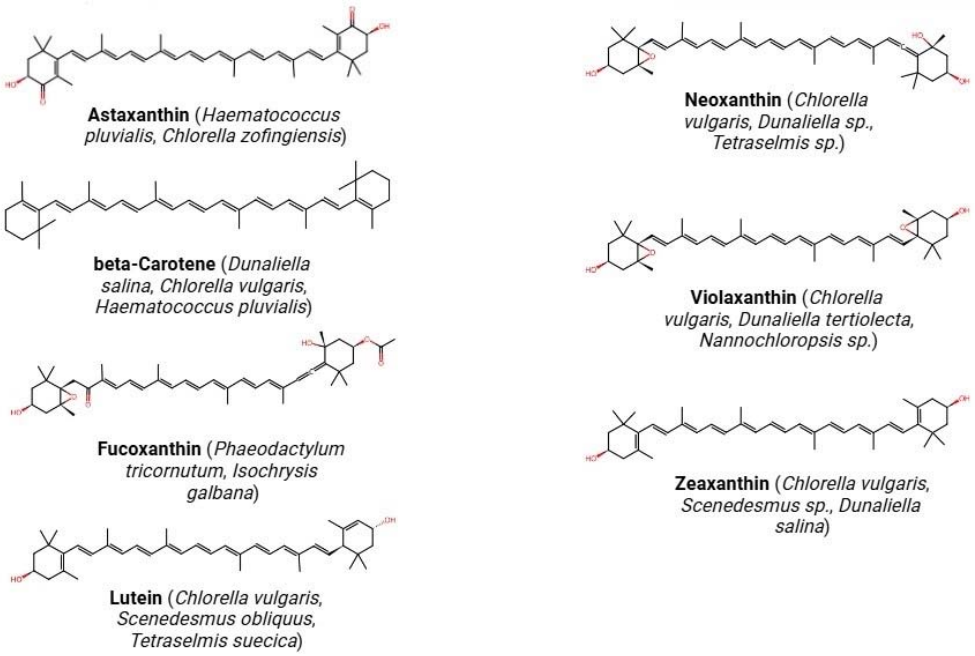



**Figure 4.** Bioactive pigments from microalgae and their potential applications in the food industry.

### *3.5. Antioxidants*

Astaxanthin, a potent antioxidant produced by *Haematococcus* spp., protects against oxidative stress, degrades macular tissues and proteins, and inhibits the formation of inflammatory substances [137]. Among the 400 known carotenoids, several compounds, including β-carotene, lutein, lycopene, astaxanthin, bixin, and zeaxanthin, are used as natural colorants and additives in the food industry. Humans convert β-carotene into vitamin A, which provides numerous health benefits, including immune system function and anti-inflammatory, antitumor, and anticarcinogenic effects [149]. Microalgae contain both water-soluble vitamins (B and C) and fat-soluble vitamins (A and E), which attract vegetarians due to the presence of vitamin B12, which is typically obtained from meat [150]. The antioxidant properties of microalgae contribute to various health benefits, such as protecting against photo-oxidation and UV radiation, slowing the aging process, enhancing the immune response, supporting liver function, and promoting eye and prostate health [151].

## 4. Microalgal Incorporation into Foods with Potential Health Benefits

When developing food products containing microalgae, it is important to consider factors such as market awareness, consumer interest, accessibility to bioactive compounds, economic viability, product durability, and longevity. Owing to stringent food safety regulations, only a limited number of microalgal species have been approved for human consumption [65]. These species include *A. platensis* [2], *Schizochytrium* sp. [152], *Scenedesmus* spp. [153], *Chlorella* spp. [154], *H. pluvialis* [155], *D. salina* [156], *Porphyridium purpureum* [157], and *T. chuii* [158]. The food industry can utilize microalgae as functional ingredients because of their high content of biologically active compounds. They meet consumer demands for nutritious, health-beneficial, sustainable, convenient, and easy-to-prepare foods [159]. Modern consumers are increasingly discerning their food choices and seeking cost-effective, high-quality products that provide additional benefits beyond the standard expectations [141]. These demands require continuous scientific and technological advancements, increased investments in product development, and targeted marketing in the food industry [155]. Recently developed food products, including those containing microalgae, are listed in Table 4.

**Table 4.** Newly developed food products incorporating microalgae.

| Product | Microalgae | Biomass Addition | Benefits | References |
|---|---|---|---|---|
| Butter cookies | *Chlorella vulgaris* | 0.5–3.0% (*w*/*w*) | Techno-functional properties | [160] |
| Bread | *Microchloropsis gaditana*<br>*Tetraselmis chuii*<br>*C. vulgaris* | - | Protein enrichment, techno-functional properties | [161] |
| Snacks | *Arthrospira platensis* | 2.6% (*w*/*w*) | Enhanced nutritional value (including proteins, fats, and minerals), physical properties (such as expansion ratio, density, firmness, water absorption and solubility indices, structural composition, and color measurements), and sensory qualities (encompassing aroma, appearance, flavor, consistency, overall likeability, and willingness to purchase) | [162] |
| Pasta | *Dunaliella salina* | 1–3% (*w*/*w*) | Improved proteins, fats, ash, minerals (calcium, iron, magnesium, and potassium), pigments (chlorophyll a, chlorophyll b, and carotene), and unsaturated fatty acids | [163] |
| Yogurt | *Isochrysis galbana* | 2% (*w*/*w*) | Enriched ω3 -polyunsaturated fatty acid contents of oleic, linoleic, α-linolenic acid, stearidonic, and docosahexaenoic acids | [164] |
| Cheese | *C. vulgaris* | 2–4% (*m*/*v*) | Improved nutritional profile, including protein and minerals (Mg, P, S, Cu, Zn, Fe, and Mn); improved bioactivity of antioxidant | [154] |

### 4.1. Microalgal PUFA Incorporated into Different Foods

The protective effects of maintaining a proper balance between omega-3 and omega-6 fatty acids in the diet to reduce the risk of diseases—such as cancer [165], type 2 diabetes [166], inflammatory and cardiovascular diseases [167], obesity [109], and osteoporosis [168]—are well documented. This explains the recent high demand for products that contain these bioactive compounds. Babuskin et al. [169] demonstrated that the microalga *Nannochloropsis oculata* can be used as a source of EPA and DHA in cookies and pasta. When 1% *N. oculata* (*w*/*w*) was added, the resulting products contained 98 and 63 mg 100 $g^{-1}$ of EPA and DHA, respectively, effectively creating functional foods rich in omega-3 fatty acids. This study also revealed that incorporating microalgal biomass enhanced the firmness of both cookies and pasta, whereas their color remained stable for two months. An untrained panel conducted a sensory evaluation that revealed a preference for cookies without microalgae. However, positive responses were obtained for products containing 1–2% (*w*/*w*) of *N. oculata*. Notably, the addition of 3% (*w*/*w*) *N. oculata* imparted a fishy taste and reduced the overall appreciation of the products. A similar pattern was observed for pasta, but tasters found that the addition of *N. oculata* microalgae was more favorable, with positive results at concentrations up to 3%. These sensory impacts are crucial to consider in food product development as they can influence consumer acceptance and market success.

The following section discusses the use of microalgal oil to enrich various food products. For instance, *Schizochytrium* sp. oil has been used to enhance the omega-3 content in dry fermented sausages by partially substituting pork backfat [170]. Furthermore, microalgal oil emulsions have been used to fortify dairy products such as strawberry-flavored yogurt, ice cream, and milk [171]. However, yogurt and ice cream enriched with omega-3 were found to have a strong fishy flavor, which was moderately appealing to trained panelists [65]. Additionally, oil enriched in DHA and EPA extracted from *Schizochytrium* sp. can be incorporated into various food products such as dairy and cheese products, dairy analogs, spreadable fats and dressings, breakfast cereals, food supplements, weight-reduction diets, nutritional foods, bakery products, cereal bars, cooking fats, non-alcoholic beverages, infant formula, and processed cereal-based foods [65]. These studies highlight the potential of microalgae to enhance the sensory characteristics of food products, inspiring further exploration and innovation in the field of food science. Additionally, the inclusion of *D. salina* in pasta has been shown to enhance its nutritional composition by increasing its mineral, phytochemical, and unsaturated fatty acid contents [163].

### 4.2. Microalgae Incorporated into Dairy and Probiotic Products

The introduction of microalgae into fermented foods, such as yogurt and cheese, establishes a novel category of nutrient-dense products by merging lactic acid bacteria with naturally occurring bioactive compounds [172]. Processed cheese spread enriched with *C. vulgaris* (2, 4, and 6% *w*/*w*) demonstrated increased concentrations of K, Zn, Mg, Se, and Fe, along with superior antioxidant capacity [173]. Fish jerky supplemented with *Sargassum wightii* (0%, 3%, and 5% *w*/*w*) showed higher levels of dietary fiber, macronutrients, and micronutrients, as well as improved antioxidant and antimicrobial characteristics [174]. A functional yogurt was developed to deliver *Pavlova lutheri* omega-3-rich lipid extract, which increased yogurt n-3 PUFA content without affecting its quality. The extract also demonstrated potent anti-inflammatory activity in vitro, thus, benefiting consumer health. However, sensory evaluation indicated low consumer acceptance, indicating the need for additional studies to enhance the sensory quality. This pioneering study on the incorporation of microalgae into yogurt suggests opportunities for future product development [175]. Research has shown that yogurt containing nanoemulsions exhibits markedly increased bioavailability of n-3 PUFA compared to regular yogurts. These findings suggest that

nanoemulsion technology can be used to enhance the bioavailability of omega-3 fatty acids in innovative food items. There is a growing market demand for products featuring plant-based sources of n-3 PUFA, as vegetarians often struggle to meet the recommended dietary guidelines. The authors proposed that such products might help bridge this nutritional gap [176].

### *4.3. Microalgae Incorporated into Pasta, Baked Goods, Condiments, and Beverages*

Increasing attention is being paid to the development of novel food items, such as pasta, biscuits, bread, noodles, snacks, candy, drinks, soft drinks, soups, and sauces [65,163]. The incorporation of 10% *A. platensis* into conventional bread resulted in higher protein and volatile compound contents, as well as longer shelf life, without compromising sensory evaluation [177]. Moreover, the incorporation of *Chlorella* into white bread enhanced its volume and color without significantly affecting the texture or flavor. Bread containing 0.2% *Chlorella* powder received high sensory scores, confirming the palatability of these innovative products [178]. Furthermore, cookies and pasta enriched with *N. oculata* showed high PUFA concentrations, with 3% biomass-enriched cookies containing 298 mg 100 $g^{-1}$ of DHA + EPA. Sensory evaluations were consistently positive for cookies and pasta enriched with up to 2% and 3% biomass, respectively [169].

Researchers have developed novel 3D-printed cookies enriched with functional compounds using microalgae, such as *A. platensis*, *C. vulgaris* [179], *H. pluvialis* [180], and a combination of *A. platensis* and *D. salina* [181]. The incorporation of 2.6% *Arthrospira* sp. into snack products resulted in enhanced nutritional value, with a protein content of 22.6%, lipids of 28.1%, and minerals of 46.4%. These snacks maintained their physical and sensory characteristics, achieving an acceptability index of 82% throughout the one-year storage period [162]. Additionally, the incorporation of *Arthrospira* marginally increased the protein content and altered the color of cheese. Cheeses containing 0.25% and 0.5% *Arthrospira* were preferred because of their milder odor and taste [182]. Adding 4% *A. platensis* to white chocolate led to notable increases in several components including total fat, LA, protein, total amino acids, lipids, and minerals. The products were distinguished using principal component analysis, which examined their physical, biochemical, and nutritional properties and explained 99.86% of the overall variation [183].

Although the use of microalgae in food products provides numerous benefits, there are some challenges and limitations. However, ongoing research and development are addressing these challenges, and the potential for innovative food products enriched with microalgae remains promising in the future. Microalgal species of the Chlorophyceae family, such as *Chlorella*, *Scenedesmus*, and *Chlorococcum*, can be combined with *Saccharomyces cerevisiae* to produce alcoholic drinks with pleasant wine-like tastes [184]. Research on the interaction between pea proteins and microalgal biomass indicates that biomass does not compromise the product texture. Instead, it may work synergistically to improve the texture and sensory characteristics [185]. Green and orange *C. vulgaris* as well as red *H. pluvialis* biomass are appropriate for producing oil-in-water vegetable food emulsions that provide stable color, desirable texture, and antioxidant benefits [186]. *Aerodramus maxima* and *Diacronema vlkianum* have been used to develop novel vegetable gel desserts high in PUFAs with enhanced textures [187]. Batista et al. [188] investigated the effects of incorporating *H. pluvialis* and *A. maxima* on the viscoelastic properties of vegetarian gel foods to determine the optimal conditions for these products.

## 5. Absorption and Availability of Bioactive Components from Microalgae

According to the FDA's definition, bioavailability refers to "the rate and degree to which the bioactive substance is absorbed and becomes accessible at the intended site of action" [189]. Bioavailability after consumption encompasses several processes, including digestion and dissolution in the gastrointestinal system, absorption through the intestinal lining, distribution via the bloodstream, and utilization at the intended site. This concept can be further categorized into two components. Bioaccessibility refers to the release of compounds into the digestive tract for efficient absorption into the bloodstream. The second is bioactivity, which involves absorption in the intestine, movement to the target location, metabolic transformation, and subsequent physiological effects [136]. Various in vitro and in vivo studies have assessed the absorption, accessibility, and biological effects of substances, underscoring the importance of standardizing data to ensure consistency and reliability. Current bioavailability data often concentrates on seaweeds and algal supplements, with limited knowledge of microalgal compounds, especially when they are incorporated into food matrices. Key considerations include the effects of food processing techniques on algal compounds, their interaction with the food matrix, and their assimilation during digestion, including their interactions with the gut microbiome [190].

The bioavailability of PUFAs is influenced by their distribution across various lipid classes (polar and neutral), positioning within triacylglycerols [121,191], and association with phospholipids and glycolipids [122,192]. In *Nannochloropsis* cells experiencing nutrient deprivation, neutral lipids, which function as storage molecules, comprise more than 90% of triacylglycerols. These triacylglycerols are abundant in C16 fatty acids but have limited utility as food components. During starvation, the breakdown of polar lipids (structural components) and the transformation and reallocation of PUFAs such as EPA may affect the distribution of ω-3 fatty acids among lipid classes, potentially modifying their bioavailability in food products [193]. The arrangement of fatty acids in triacylglycerols affects their nutritional quality, absorption, and metabolism. PUFAs located at the SN-2 position provide better nutritional value and are more readily absorbed than randomly distributed PUFAs [191]. Furthermore, PUFAs linked to phospholipids exhibit higher bioavailability than triacylglycerols [194].

Research has shown that incorporating *D. vlkianum* (101 mg $kg^{-1}$ EPA + DHA, equivalent to 24.2 g microalga in humans) into meals leads to increased fatty acid levels in various tissues and sera [195]. Investigations into DHA supplements derived from *C. cohnii*, *Schizochytrium*, and a fortified snack bar revealed comparable bioavailability across all forms, with a clear dose–response relationship. The similarity in plasma DHA levels between capsules and fortified snack bars suggests that consuming DHA in food may enhance absorption [196]. Another study focusing on algal-DHA oil and orange juice further supported the idea that food consumption may improve DHA uptake [197]. The food matrix is known to influence ω-3 bioavailability; for instance, utilizing nanoemulsion technology with yogurt as a carrier resulted in a rapid increase in DHA concentration [176].

Fabregas and Herrero [198] found that *T. suecica*, *I. galbana*, *Dunaliella tertiolecta*, and *Chlorellla stigmatophora* contain higher concentrations of vitamins E, B1, and β-carotene than other food sources. The absorption of fat-soluble vitamins is significantly enhanced by the consumption of lipid-rich foods, a dietary habit that can positively influence nutrient uptake [199]. Furthermore, the bioavailability of vitamins increases when microalgal biomass is disrupted [200]. Carotenoid absorption efficiency is affected by various factors including the food matrix, processing techniques, other food components, and an individual's nutritional and physiological state [201]. Goh et al. [200] demonstrated that dried extracts of *N. oculata* and *Chaetoceros calcitrans* exhibited significantly higher bioaccessibility than their powdered forms. Furthermore, Gille et al. [202] reported that biomass treatment influenced

carotenoid bioaccessibility in two microalgae species. Although *C. reinhardtii* effectively provides carotenoids without processing, *C. vulgaris* requires additional treatment. Moreover, the unicellular structure of *Arthrospira* allows for easier digestion of β-carotene than that in leafy green vegetables [203]. Despite the widespread production of *Arthrospira*, research on vitamin A bioavailability in humans remains limited, with most studies focusing on supplements rather than whole food sources.

The bioavailability of astaxanthin from *Haematococcus* is restricted by the physical barrier of cysts. This constraint can be addressed by mechanical disruption and autoclaving [204]. Notably, astaxanthin absorption is enhanced when it is consumed after meals [205]. The development of effective microalgal-based products require the consideration of multiple factors. For instance, optimal nutrient levels or deprivation during cultivation can influence the fatty acid composition of lipids and alter the positioning of PUFAs in triacylglycerols, thereby affecting their bioavailability. A key challenge in microalgal cultivation is to maintain a balance between protein and lipid production during nutrient deprivation. The chemical structure of microalgal compounds plays a crucial role in their release and availability, making it essential to understand these structures. Various biomass treatment methods are needed to enhance the bioavailability of intracellular compounds. Furthermore, the incorporation of microalgae into food matrices is important because dietary lipids often boost the bioavailability of compounds such as vitamins.

### *5.1. Advanced Strategies to Improve Bioavailability*

To further address bioavailability challenges, several advanced strategies have been explored, including microencapsulation, lipid structural modification, and fermentation.

#### 5.1.1. Microencapsulation

Microencapsulation is an advanced technique that significantly enhances the bioavailability of bioactive compounds derived from microalgae by encapsulating them in protective matrices. This approach protects bioactive compounds from environmental degradation while facilitating improved absorption within the human gastrointestinal system. A study reported that the microencapsulation of esterified astaxanthin extracted from microalgae using complex coacervation with whey protein and Arabic gum significantly enhanced its bioavailability [206], indicating that this encapsulation technique provided protection against oxidative degradation and improved the stability of astaxanthin, thereby improving its absorption efficiency in the gastrointestinal tract. Similarly, Koo et al. [207] developed alginate–casein nanoparticles to encapsulate fucoxanthin derived from *Phaeodactylum tricornutum*. The encapsulated fucoxanthin showed enhanced stability and a controlled release profile, resulting in improved bioavailability compared to the unencapsulated form. Furthermore, research on the microencapsulation of *C. vulgaris* through complex coacervation effectively protected its bioactive compounds against environmental factors, thereby improving their stability and potential bioavailability in functional food applications [208]. These studies highlight the effectiveness of microencapsulation in preserving the structural integrity and enhancing the bioavailability of microalgal bioactive molecules, making this technique a promising strategy for the development of functional foods and nutraceuticals.

#### 5.1.2. Lipid Structural Modification

Lipid structural modifications can significantly enhance the bioavailability of bioactive compounds derived from microalgae by improving their digestion and absorption in the gastrointestinal tract. One of the most effective strategies involves the formulation of excipient emulsions with specific lipid compositions to facilitate the solubilization and uptake of bioactive molecules. For instance, Yuan et al. [209] demonstrated the influence of lipid type on carotenoid bioaccessibility from spinach and reported that excipient emulsions contain-

ing medium-chain triglycerides (MCTs) showed higher lipid digestion rates and improved carotenoid bioaccessibility compared to emulsions formulated with long-chain triglycerides (LCTs). Although this study focused on plant-derived carotenoids, its underlying principles can be applied to microalgal-derived bioactive molecules. Modifying the lipid composition of delivery systems, such as incorporating MCTs or optimizing the lipid type ratio, can improve the solubilization, stability, and absorption of bioactive compounds from microalgae. However, further research is required to explore the specific impact of lipid structural modifications on the bioavailability of diverse microalgal bioactive compounds.

#### 5.1.3. Fermentation

Fermentation is a valuable biotechnological approach for enhancing the bioavailability of bioactive compounds derived from microalgae. This process involves the metabolic activity of microorganisms, which can modify the structural composition of microalgal compounds, thereby improving their digestibility and absorption in the human gastrointestinal tract. Demarco et al. [210] reported that the bioavailability of microalgae-derived compounds is influenced by several factors, including cell wall disruption techniques and the presence of specific bioactive substances. Bürck et al. [211] demonstrated the potential of microbial fermentation for developing safe, nutritious, and sustainable food products incorporating microalgae. This study highlights the role of fermentation in enhancing the bioavailability of microalgal metabolites, thereby contributing to the advancement of functional foods with enhanced health benefits. These studies indicate that fermentation can be an effective strategy for improving the bioavailability of microalgal bioactive molecules.

## 6. Challenges in Food Formulation with Microalgae

The incorporation of microalgae into functional foods faces numerous obstacles, including elevated production costs, unappealing taste profiles, degradation of active ingredients during manufacturing, consumer skepticism, and pronounced pigmentation of the final product. Although the demand for microalgae-based products is growing, the industry faces several challenges in meeting this demand. The economic viability of large-scale microalgal biomass production, particularly in terms of cultivation and harvesting, remains unclear. Previous studies have extensively discussed the costs associated with production, harvesting, and processing, identifying them as significant barriers to widespread adoption [212]. Therefore, it is important to consider the fundamental recommendations for establishing an efficient and cost-effective process for algal biomass production. In particular, harvesting is costly, accounting for 20–30% of the total cost [213,214]. Currently, energy-intensive harvesting methods such as flotation, centrifugation, filtration, and electricity-based techniques account for 90% of the expenses associated with the extraction of microalgal biomass from open ponds [213,214]. Future biotechnologies should integrate eco-friendly and cost-effective methods to produce, harvest, and process microalgae.

### *6.1. Challenges for Sensory Qualities of Food with Microalgae*

A significant challenge facing the microalgae sector is the unpleasant sensory attributes of microalgae-derived products [215]. For example, dried *Arthrospira* products such as powders, tablets, and beverages often have a fishy smell or taste [216]. Fresh *Arthrospira* has minimal impact on the smell and flavor of food or drinks. However, when unprocessed microalgae components are present at higher concentrations, they can introduce an unpleasant taste, making food unappealing to most consumers, especially those who are unfamiliar with algal products. Sensory evaluation of yogurt with *A. platensis* and *C. vulgaris* showed that *A. platensis* has a more unpleasant flavor than *C. vulgaris* [217]. Oxidation of PUFAs and other microalgal components results in an unpleasant flavor. Incorporating varying

concentrations of *Arthrospira* (0.25, 0.5, 0.75, and 1%) into yogurt influences its fermentation, texture, and nutritional and sensory characteristics [218]. The addition of 0.25% *Arthrospira* preserved the texture and sensory acceptability of the final yogurt. Gyenis et al. [219] demonstrated that milk fermented with 3 g/dm3 of microalgal biomass yielded optimal sensory qualities and was economically viable. However, decreasing the microalgae content in food items to minimize undesirable taste and odor also reduces the levels of proteins and other bioactive compounds. Baked goods such as bread, cookies, and pasta are more amenable to microalgae incorporation than yogurt [216,220]. Batista et al. [221] reported that cookies containing 2% (*w*/*w*) *Arthrospira* exhibited favorable flavor outcomes.

A major obstacle in incorporating microalgal dry biomass into food products is its strong coloration, which can negatively affect the visual appeal of certain foods such as bread and dairy items. This issue is less problematic for products, such as pasta, which are commonly available in various hues. An effective technique to disguise the microalgal flavor involves spray-drying microencapsulation, with octenyl succinic anhydride starch serving as an efficient coating material. Research has shown that adding 20% (*w*/*w*) microencapsulated *Arthrospira* to wheat cookies did not significantly alter purchase intent or overall acceptance compared with the control samples. This addition also resulted in a 40% increase in protein content and a 70% increase in ash content, which is consistent with previous findings [222]. Recent developments have addressed the issue of the vibrant color of microalgae. The European Food Safety Authority has approved two pale-colored *Chlorella* powder products with reduced chlorophyll content for use as food ingredients and supplements [223]. These products provide a more neutral appearance and greater consumer appeal than traditional dark green alternatives do. Furthermore, studies have demonstrated that the C/N ratio in the cultivation medium can influence the color of microalgal biomass [224,225].

The acceptance of new dietary practices involving unfamiliar foods may differ among individuals, and is influenced by their cultural backgrounds and potential future prospects. The findings presented here can also be applied to other European nations. One important factor is the tolerance of consumers to the taste of microalgae-based foods [216,220]. Key elements in developing this market include the type of microalgae used, preparation methods (e.g., dried powder or processed), ingredient combinations, and the final product form. Challenges, such as strong smells and fishy flavors, are noteworthy. Participants' attitudes toward unfamiliar foods were tested, as food neophobia can impact acceptance of novel foods [216,220]. Consumers perceive a product as healthier and are willing to pay more for it, which is beneficial for promotion and sales. The market for microalgae-based foods also encounters challenges in terms of customer acceptability, production capacity, and regulatory issues, as laws vary by country. Incorporating microalgae can influence the absorption and use of bioactive substances, necessitating a comprehensive examination of health benefits to market these foods as "functional foods". The type of product and amount of microalgae added also influence consumer acceptance, underscoring the importance of promoting microalgae-based foods. Evaluating the present market position and ongoing research on microalgae-derived products is essential, as it identifies the challenges and barriers that hinder their adoption as food components. Given that conventional food production techniques cannot satisfy global needs, it is imperative that manufacturing processes become more environment-friendly and expandable.

### *6.2. Food Safety and Risk Factors*

The safety of algal foods is influenced by three main factors: physical and chemical pollution, as well as microbiological contamination [226]. These factors create the need for new technologies that can quickly detect contaminants. Recent advancements have

led to the development of improved techniques for detecting heavy metals, algal toxins, and other pollutants. Future detection methods such as artificial intelligence, biosensors, and molecular biology are expected to be cost-effective, fast, and safe. It is important that microalgal biomass, supplements, and biochemical compounds derived from microalgae comply with the existing food regulations to ensure that they are free from contamination. For example, authorities do not allow solvent residues, which may occur during the production of fatty acids by microalgae [142].

### 6.3. Challenges in Maintaining Consistent Nutritional Value of Microalgae

Environmental factors, such as light, humidity, pH, and elevated temperatures, influence the composition of microalgae, rendering them unstable [206]. Maintaining the stability of biochemical components is essential to maximize their utility. Research has proposed encasing microalgae bioactive extracts, including carotenoids, astaxanthin, and free fatty acids, with a biopolymer layer to address their poor stabilities. This protective coating enhances resilience under various conditions [227]. Encapsulation techniques were used to ensure drug stability and bioavailability. This process involves incorporating a specific ingredient into a matrix, whereas an "encapsulation system" refers to a mechanism designed to encapsulate, safeguard, and release target active compounds [228].

Food processing significantly impacts the stability of microalgal pigments like chlorophylls, carotenoids, phycobiliproteins, and astaxanthin. Chlorophylls degrade under acidic conditions and light exposure, though encapsulation can enhance stability [229]. Carotenoids are prone to oxidation and heat-induced degradation, but encapsulation and freeze-drying help preserve them [230]. Phycobiliproteins, such as phycocyanins, are sensitive to heat and pH changes, with high-pressure processing affecting their functionality [231]. Astaxanthin also degrades with heat and oxidation, but microencapsulation and emulsions improve its stability [232]. Additionally, drying methods influence pigment retention, with spray-drying increasing oxidation susceptibility and freeze-drying leading to lipid breakdown [233]. Optimizing processing and storage techniques is essential to maintaining the bioactivity and functionality of these compounds in food products.

Omega-3 polyunsaturated fatty acids (n-3 PUFAs) derived from microalgae are highly susceptible to oxidation during food processing and storage, which can degrade their nutritional quality and lead to the formation of undesirable compounds. Thermal processing and mechanical treatments can reduce n-3 PUFA content, particularly when free fatty acids are present, as observed in model systems enriched with various microalgal species [234]. To mitigate oxidation, microencapsulation techniques, such as spray drying, have been employed to protect these fatty acids, enhancing their stability and bioavailability. However, the high temperatures involved in spray drying may still pose challenges to PUFA stability [235]. Additionally, the oxidative stability of omega-3 oils in nanoemulsions varies depending on factors like emulsifier type and storage conditions. For instance, nanoemulsions stabilized with lecithin exhibited larger droplet sizes and higher volatile compound formation at elevated temperatures, indicating increased oxidation [236]. Therefore, optimizing processing methods and storage conditions is crucial to preserve the integrity of omega-3 fatty acids in microalgal-derived food products.

The stability of microalgal proteins during processing is influenced by factors such as temperature, pH, and salt concentration. For instance, protein hydrolysates from *Arthrospira* sp. demonstrated stable antioxidant activity when subjected to freezing (−18 °C), pasteurization (63 °C), and cooking (100 °C) temperatures, indicating their potential for incorporation into various food products. However, exposure to room temperature storage and cooking temperatures notably decreased their ability to scavenge ABTS radicals, suggesting that elevated temperatures may affect peptide structures and reduce antioxidant efficacy.

Additionally, acidic conditions (pH 4) and low acidity (pH 6) influenced the antioxidant mechanisms differently, affecting the peptides' electron transfer capabilities. Salt concentrations up to 6 wt% did not significantly impact DPPH-radical-scavenging activity, but an 8 wt% NaCl concentration increased antioxidant activity by approximately 37%, possibly due to enhanced exposure of functional groups capable of releasing hydrogen ions [237].

Polysaccharides in microalgae, such as those found in *Arthrospira*, are susceptible to degradation during drying processes. High temperatures can cause denaturation or deactivation of these active ingredients, thereby affecting their content and biological activity in the final product. For example, phycocyanin, a natural blue pigment with notable antioxidant capacity, experiences a nearly 20% reduction in total content when subjected to high-temperature drying at 200 °C [238].

## 7. Conclusions

Microalgae represent a sustainable marine resource with a significant potential for creating innovative food products that prioritize health, nutrition, and environmental sustainability. While there is growing interest from both scientific and industrial sectors, as well as increasing consumer demand, additional investment in applied and mechanistic scientific research remains essential. This is particularly critical for advancing technologies to improve product safety and sensory attributes, without reducing the beneficial quantities of microalgal components. To prevent biological and chemical hazards, legislative measures must be implemented, including monitoring programs, labeling procedures, and good manufacturing practices. Future studies should focus on examining the bioaccessibility and bioavailability of marine bioactive compounds within various food matrices to optimize their nutritional and health advantages. These insights are vital for developing food products that can function as preventive or therapeutic agents against chronic non-communicable diseases.

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