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Review

Microalgae as Functional Food Ingredients: Nutritional Benefits, Challenges, and Regulatory Considerations for Safe Consumption

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Abstract: The projected global population is expected to reach 9.7 billion by 2050, necessitating a significant increase in food production. Malnutrition remains a global health challenge that contributes to over 3.5 million deaths annually and accounts for 45% of all child mortalities. Microalgae, including cyanobacteria, are a promising solution because of their rich composition of bioactive compounds such as polyunsaturated fatty acids, carotenoids, proteins, vitamins, and minerals. These biomolecules provide various health benefits, including antioxidant, antidiabetic, anticancer, anti-inflammatory, and cardioprotective properties, making microalgal biomass a valuable ingredient in functional food formulations. However, the large-scale adoption of microalgae for food production faces several challenges, including species-specific variations in biochemical composition, inconsistencies in biomass yield, structural alterations during extraction and purification, sensory issues, and bioprocessing inefficiencies. Furthermore, regulatory challenges and concerns regarding bioavailability and safety continue to limit their widespread acceptance. Despite these limitations, microalgal bioactives have significant potential for the development of next-generation nutraceuticals and functional foods. This review examines the bioactive compounds found in microalgae, detailing their biological activities and functional applications in the food industry. Additionally, it explores the key challenges preventing their integration into food products and proposes strategies to overcome these challenges, ultimately facilitating the commercialization of microalgae as a sustainable and health-promoting food source.

Keywords: biomass; bioactive compounds; nutrition; innovative food products; peptides; proteins; health benefits; food formulations

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1. Introduction

The growing interest in functional foods has led to extensive research on the physiological effects of naturally derived bioactive components with high nutritional value [1]. Microalgae have emerged as a promising source of novel food ingredients because of

their rich and balanced nutritional composition [2]. Microalgal biomass is composed of a diverse range of nutrients, including 40–70% proteins [2–4], 12–30% carbohydrates [5,6], 20–50% lipids [7,8], 8–14% carotenoids [9,10], and substantial quantities of essential vitamins such as B1, B2, B3, B6, B12, E, K, and D [11]. Historical evidence suggests that microalgae, particularly *Nostoc* spp. (cyanobacteria), have been consumed by humans for over two millennia, emphasizing their longstanding role as dietary supplements [12]. The commercial microalgal industry predominantly cultivates species such as *Arthrospira*, *Chlorella*, *Dunaliella*, *Nannochloris*, *Nitzschia*, *Crypthecodinium*, *Schizochytrium*, *Tetraselmis*, and *Skeletonema* for their potential applications in the production of health-promoting ingredients [13]. These microalgal-derived bioactive components are utilized as whole biomass or extracts and serve as valuable sources of pharmaceuticals, nutraceuticals, and functional food products [14]. Bioactive compounds derived from these species exhibit a wide range of pharmacological activities, including antioxidant, antidiabetic, anticancer, anti-inflammatory, and cardioprotective effects. Additionally, these compounds are employed in diverse sectors such as human nutrition, animal and aquaculture feeds, cosmetics, and biofertilizers [15]. The global market for microalgae-based products, currently valued at approximately US $4.96 billion, is expected to grow at a compound annual growth rate (CAGR) of 4.8% to reach US $9.1 billion by 2032 [16].

The integration of microalgal biomass into functional foods has been extensively explored, and studies have demonstrated its potential to improve the texture, stability, and bioavailability of essential nutrients [17]. Microalgae-enriched foods, such as bread, pasta, cookies, dairy products, and beverages, have been shown to retain their sensory properties while providing enhanced nutritional value [18]. However, the widespread adoption of microalgae in the food industry faces challenges, including sensory limitations such as color and taste alterations, processing stability, and consumer acceptance [19,20]. Advances in food technology, including innovative processing techniques and formulation strategies, are essential for optimizing the incorporation of microalgae into various food matrices while still preserving their functional properties [21]. Furthermore, regulatory approval and safety considerations play critical roles in determining the commercialization potential of microalgae-based food products [22]. However, several microalgal species, including *Arthrospira*, *Chlorella*, *Dunaliella*, *Schizochytrium*, *Porphyridium cruentum*, and *Crypthecodinium cohnii*, have been categorized as Generally Recognized as Safe (GRAS) by regulatory authorities in the U.S. Food and Drug Administration (FDA), European Food Safety Authority (EFSA), Australia, and New Zealand, permitting their consumption in global markets [19,23–25]. Despite this regulatory progress, further research is necessary to ensure consistent quality, address potential contamination risks, and optimize large-scale cultivation and processing techniques [26,27].

This study aimed to comprehensively examine the potential of microalgae as functional food ingredients, focusing on their nutritional benefits, challenges in commercialization, and necessary regulatory considerations to ensure their safe and effective utilization in food systems. Moreover, we seek to contribute to the growing body of knowledge surrounding microalgae as a sustainable solution for enhancing food security and promoting human health.

2. Bioactive Components in Microalgae and Their Health Benefits

2.1. Proteins, Peptides, and Amino Acids

Proteins are essential macromolecules that provide nitrogen and amino acids, which are critical for various metabolic functions, including cellular growth, immune responses, and reproductive processes. Proteins are fundamental components of enzymes, hormones, cell membranes, and transport proteins, all of which are involved in the regulation and movement of metabolites within the circulatory system [28]. Certain amino acids, such as histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine, cannot be synthesized endogenously by the human body. Therefore, these amino acids must be obtained through food consumption. Moreover, conditionally essential amino acids, including arginine, cysteine, glutamine, glycine, proline, and tyrosine, may not be synthesized in sufficient quantities during specific physiological periods of growth, such as pregnancy, rapid growth in infants, chronic diseases (e.g., kidney or liver disorders), metabolic stress due to severe illness, or recovery from trauma [29]. In this context, protein-rich microalgae are regarded as an excellent source of proteins, peptides, and essential and non-essential amino acids (Table 1). However, it is important to avoid certain toxin-producing microalgal species, such as cyanobacteria and dinoflagellates, which are known to produce harmful toxins (e.g., aphanotoxins and okadaic acid) that can cause severe health complications, including gastrointestinal disturbances and paresthesia.

Table 1. Protein and amino acid content in different microalgal species.

Microalgal Species	Protein Content (%)	Essential Amino Acids (g 100 g Protein^{-1} DW)									Non-Essential Amino Acids (g 100 g Protein^{-1} DW)									References
		Thr	Val	Met	Iso	Leu	Phe	His	Lys	Arg	Try	Asp	Ser	Glu	Pro	Gly	Ala	Cys	Tyr	
Acutodesmus obliquus	40.34	5.28	5.88	1.64	3.48	8.38	4.34	2.04	5.7	7.40	1.97	1.00	5.02	12.62	5.90	6.32	8.34	1.08	4.35	[30]
Arthrospira platensis	-	4.57	7.81	1.93	4.48	9.81	7.85	2.19	7.11	6.02	1.16	10.12	3.31	14.36	5.17	5.25	11.48	1.94	7.85	[31]
Botryococcus braunii	39.9	3.7	4.4	2.5	3.4	7.1	4.4	1.5	4.7	20.5	2.2	8.7	3.5	12.7	4.6	4.9	6.4	1.4	2.8	[2]
Chlorella vulgaris	-	4.16	6.37	2.52	3.36	8.41	6.17	1.52	5.35	7.33	0.21	8.54	4.34	10.28	5.08	7.14	10.82	1.47	4.34	[31]
Chlorella pyrenoidosa	-	3.45	5.17	3.30	6.20	3.44	3.83	1.64	8.14	5.91	-	8.12	2.79	7.87	-	9.73	5.08	2.82	1.22	[3]
Chlorella sorokiniana	5.02	4.29	5.80	1.87	3.61	9.19	5.37	1.77	5.19	8.79	2.33	1.03	5.09	11.82	5.35	5.82	8.42	1.02	4.43	[30]
Dunaliella salina	-	5.16	7.23	2.79	4.09	9.58	6.98	1.73	5.99	8.16	0.18	9.56	4.81	12.41	5.23	8.71	10.99	1.63	4.86	[31]
Nannochloropsis granulata	33.5	5.4	7.1	3.5	5.6	11.0	6.2	2.3	8.5	7.4	2.8	11.4	5.6	14.1	11.2	7.5	7.1	1.6	4.2	[2]
Nostoc sp.	-	5.31	7.15	2.23	3.68	9.41	7.15	2.01	6.47	6.15	1.02	9.18	3.16	12.38	5.28	6.54	9.88	1.54	6.84	[30]
Phaeodactylum tricornutum	39.6	4.8	5.1	2.7	4.6	7.0	4.8	1.5	6.4	5.7	2.6	11.6	4.8	18.8	7.1	5.5	7.3	1.5	3.4	[2]
Pleurochrysis carterae	-	5.67	7.55	2.41	4.22	9.93	7.69	1.89	7.24	6.88	1.14	9.19	3.48	15.17	5.12	7.02	11.51	2.03	7.69	[31]
Porphyridium aerugineum	31.6	5.8	7.3	3.7	7.1	11.9	6.3	1.9	8.0	8.6	3.3	15.0	7.0	15.6	5.0	7.0	8.4	2.2	5.8	[2]
Tetraselmis chuii	46.5	4.0	4.8	2.4	3.4	7.3	4.7	1.6	5.6	9.4	2.3	14.1	4.2	12.0	3.6	6.5	6.0	2.8	3.0	[2]

Abbreviations: Thr, Threonine; Val, Valine; Met, Methionine; Iso, Isoleucine; Leu, Leucine; Phe, Phenylalanine; His, Histidine; Lys, Lysine; Arg, Arginine, Try, Tryptophan; Asp, Aspartic acid; Ser, Serine; Glu, Glutamic acid; Pro, Proline; Gly, Glycine; Ala, Alanine; Cys, Cysteine; Tyr, Tyrosine.

The utilization of protein-derived bioactive peptides as functional food ingredients is an emerging area of innovation in the food industry [32]. Bioactive peptides, consisting of 5–20 amino acids, exhibit beneficial biological activities and are increasingly being incorporated into peptide therapy because of their enhanced bioavailability, specificity, and lower allergenicity compared with conventional pharmaceutical drugs [33]. These peptides remain inactive within the primary protein structure until they are released through specific processes: (i) enzymatic hydrolysis via microbial fermentation, (ii) enzymatic hydrolysis during gastrointestinal protease activity, or (iii) proteolytic processing using exogenous enzymes [26]. Peptides were first identified in 1950 as major contributors to increased bone calcification in infants with rickets [34]. However, subsequent studies have shown that milk proteins are the major contributors to this effect in infants [35].

Peptides derived from microalgae are currently being investigated as functional ingredients for the management and treatment of various conditions, including hypertension, diabetes, inflammation, cancer, oxidative stress, and immune disorders [26,36]. For instance, microalgal peptides have demonstrated potential anti-inflammatory and antihypertensive properties, inhibiting the production of pro-inflammatory cytokines and the activity of angiotensin I-converting enzyme (ACE), both of which contribute to the exacerbation of several diseases [12]. Peptides from *Chlorella* sp. exhibit antioxidant properties, as shown by both in vitro and cell-based assays. Specifically, *Chlorella ellipsoidea* produces a pentapeptide with antioxidant activity, including peroxyl and 2, 2-Diphenyl-1-picrylhydrazyl (DPPH) radical scavenging, following peptic hydrolysis, along with intracellular radical scavenging activity in monkey kidney cells [37]. Furthermore, a peptide derived from *Chlorella pyrenoidosa* (5–10 mg L^{-1}) provides complete protection against UV irradiation-induced cytotoxicity in human skin fibroblasts for more than 72 h [38]. Proteins derived from *Nannochloropsis gaditana* have also shown antitumor activity against Caco2 (colon adenocarcinoma) and HepG-2 (hepatocellular carcinoma) cell lines [39].

Tejano et al. [40] employed proteomics and bioinformatics to extract bioactive peptides from an isolated protein fraction of *Chlorella sorokiniana*. Their analysis identified the optimal enzymes for hydrolysis and extraction, revealing peptide sequences with potential antidiabetic, antihypertensive, antiamnestic, antioxidant, and antithrombotic properties in *C. sorokiniana*. Hydrolysis of *C. sorokiniana*-derived proteins with pepsin, bromelain, and thermolysin produces bioactive peptides with varying molecular weights that demonstrate antihypertensive, antioxidant, and antibacterial activities in vitro [41]. Several bioactive peptides derived from microalgae have demonstrated significant biological activities, as summarized in Table 2.

Table 2. Microalgae-derived peptides produced using enzymatic hydrolysis found to have biological activity.

Species	Enzyme Used for Hydrolysis	Peptide Sequence	Observations	References
Arthrospira maxima	Trypsin, α-chymotrypsin, and pepsin	LDAVNR MMLDF	Anti-inflammatory effect was shown in vitro; Suppressive effect on the release of histamine and production of interleukin-8	[42]
Arthrospira platensis	Thermolysin	FSESSAPEQHY	Antioxidant	[43]
Chlorella ellipsoidea	Papain, trypsin, pepsin, and a-chymotrypsin	LNGDVW	Antioxidant	[37]
Chlorella pyrenoidosa	Pepsin and trypsin	FLKPLGSGK QIYTMGK FLFVAEAIYK QHAGTKAK	Anti-hypertensive and anti-diabetic effect; Inhibited the activity of angiotensin I-converting enzyme (ACE) and dipeptidyl peptidase-IV (DPP-IV) in vitro	[44]

Table 2. *Cont.*

Species	Enzyme Used for Hydrolysis	Peptide Sequence	Observations	References
Chlorella sorokiniana	Pepsin, bromelain, and papain	n/d	DPP IV and ACE inhibitory, antioxidant, anti-amnestic, and antithrombotic activity	[41]
Chlorella vulgaris	Pepsin	VECYGPNRPQF	Hendeca-peptide inhibit the activity of ACE; Regulated hypertension and water-fluid balance.	[45]
Isochrysis zhanjiangensis	Chymotrypsin	NDAEYGICGF	Antioxidant	[46]
Nannochloropsis oculata	Pepsin, trypsin, α-chymotrypsin, papain, alcalase, and neutrase	GMNNLTP LEQ	ACE inhibitory	[47]
Scenedesmus obliquus	Pepsin, trypsin, and papain	RKDAH	Antioxidant and antiviral activity	[48]
Tetradesmus obliquus	Alcalase	WPRGYFL GPDRPKFLGPF WYGPDRPKFL SDWDRF	Antioxidant and ACE-inhibitory	[49]

2.2. Lipids and Polyunsaturated Fatty Acids

Lipids are complex biomolecules that comprise fatty acids, sterols, waxes, hydrocarbons (both short- and long-chain), and pigments. Microalgae naturally synthesize lipids for energy storage, which also serve as key structural components of cellular membranes and signaling molecules [15]. These organisms have the potential to produce oil yields up to 23 times greater than those of palm oil and 800 times greater than those of maize [12]. The lipid content in microalgal cells typically ranges from 20 to 50% of the dry weight (DW) biomass, with accumulation levels substantially influenced by culture conditions and strain-specific factors [50]. As a result, microalgae represent a valuable source of polyunsaturated fatty acids (PUFAs), which are increasingly sought after by the healthcare and nutraceutical industries. PUFAs are long-chain hydrocarbons characterized by the presence of 18 or more unsaturated fatty acids, including omega-3 fatty acids (e.g., α-linolenic acid (ALA), eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA)) and omega-6 fatty acids (e.g., linoleic acid (LA), γ-linolenic acid (GLA), and arachidonic acid (ARA)). Notably, specific microalgal species, including *C. vulgaris* and *A. platensis*, have demonstrated superior potential to produce high yields of PUFAs compared to conventional oil plants [50,51].

Omega-3 fatty acids represent a distinct group of PUFAs, including ALA (C-18:3), which has the shortest hydrocarbon chain found in vegetable oils and nuts. In contrast, EPA (C-20:5) and DHA (C-22:6) are primarily found in fish oils [50]. PUFAs, particularly EPA and DHA, are abundant in fish and fish-derived oils because fish consume and digest microalgae in aquatic environments. Both EPA and DHA are vital for optimal brain function and are associated with the prevention of various health conditions, including coronary heart disease, myocardial infarction, inflammatory diseases, bipolar disorder, cognitive decline, aggressive behavior, and age-related maculopathy [15]. Specifically, in the context of type 2 diabetes, EPA and DHA have been shown to significantly reduce triglyceride levels, a key factor in arterial fat accumulation, thus inhibiting the onset of hypertriglyceridemia. Notably, EPA alone has demonstrated the capacity to reduce low-density lipoprotein (LDL) and total cholesterol levels while causing fewer gastrointestinal side effects than DHA [52].

The anti-inflammatory effects of EPA and DHA are mediated through multiple mechanisms, including the inhibition of leukocyte chemotaxis, reduction of adhesion molecule expression and leukocyte –endothelial interactions, disruption of lipid rafts, inhibition of nuclear factor kappa-light-chain-enhancer of activated B cells (NF-κB) activation, activation of anti-inflammatory transcription factors such as peroxisome proliferator-activated

receptor gamma (PPARγ), and binding to the G protein-coupled receptor GPCR120 [53]. Moreover, the intake of omega-3 fatty acids during lactation and pregnancy has been shown to protect newborns from allergies and is crucial for brain and retinal development [54]. Pregnant women who consume EPA and DHA supplements demonstrate improved infant outcomes, including enhanced eyesight, memory, and problem-solving abilities [55]. The World Health Organization (WHO) and the FDA recommend a daily intake of 0.2–0.5 g DHA and EPA and 1.6 g ALA for healthy individuals. For those with coronary heart disease, the recommended dosage may be increased to 1.0 g day^{-1} [56]. Higher ALA consumption (2.11 g day^{-1}) has been shown to significantly reduce the risk of peripheral neuropathy and sudden coronary artery disease by 40% [57].

Omega-6 fatty acids, including linoleic acid (LA; C18:2) and arachidonic acid (ARA; C20:4), are essential dietary components of the human body. *P. cruentum* has been identified as a significant producer of ARA, whereas other microalgal species typically produce less than 0.2% of their biomass [58]. The recommended dietary ratio of omega-3 to omega-6 fatty acids in healthy individuals typically ranges from 1:1 to 1:4. However, excessive ARA intake has been associated with a range of severe health complications, including atherosclerosis, hypertension, stroke, type 2 diabetes, cancer, elevated free fatty acid and triacylglycerol levels, and oxidative stress. These conditions significantly contribute to the development of cardiovascular diseases and other chronic health issues. In contrast, the consumption of omega-3 fatty acids, specifically EPA and DHA, can mitigate the adverse effects of excessive omega-6 intake, including the prevention of atherosclerosis. Therefore, maintaining an optimal omega-3:omega-6 ratio is critical for human health [59].

Microalgal species, including *Chlorella* sp., *Dunaliella salina*, *Nannochloropsis oculata*, *Pavlova lutheri*, and *Schizochytrium* sp., are widely recognized for their beneficial properties and are extensively utilized in the development of health-oriented products. *Chlorella* sp. has been shown to enhance immune function and is commonly employed in the industrial production of essential fatty acids, such as omega-3 and omega-6, which are key components of numerous immune-boosting dietary supplements [60]. *N. oculata* is particularly rich in omega-3 fatty acids, including EPA and DHA, which are incorporated into the production of functional foods with a range of health-promoting benefits [61].

2.3. Polysaccharides

Carbohydrates are the primary energy source produced via photosynthesis and carbon fixation in microalgal cells [62]. These compounds are typically stored as reserve materials, primarily in the form of starch (including glucose, mannose, rhamnose, xylose, and galactose) within plastids or as key constituents of the cell wall, such as cellulose, pectin, and sulfated polysaccharides [12]. The composition and metabolism of carbohydrates in microalgae vary considerably among species [63]. Carbohydrate storage capacity can differ significantly among species; for instance, the monosaccharide glucose was found to comprise 15.2% and 66.2% of the total carbohydrates in *Chlorococcum* sp. and *D. salina*, respectively [12,63]. In addition, cyanobacteria, red algae, and green algae synthesize glycogen-, floridean-, and amylopectin-like polysaccharides, respectively. Under controlled conditions, species such as *Chlamydomonas* sp., *Chlorella* sp., and *Arthrospira* sp. accumulate substantial quantities of carbohydrates [12]. *P. tricornutum* is characterized by a high hemicellulose content, predominantly composed of monosaccharides, including galactose, rhamnose, mannose, and xylose/arabinose, which are integral to the microalgal cell composition [64].

Incorporating carbohydrate-derived microalgal biomass is a promising strategy for enhancing the nutritional profile of functional foods and feed products [65] and for producing high-value compounds with applications in the pharmaceutical and cosmetic industries [66].

Among various bioactive compounds, 1,3-β-glucan has gained significant attention owing to its wide range of applications. It is used as a thickening agent in the food industry [65] and as an in vivo tumor growth inhibitor with anti-infective properties in the healthcare industry [12]. Notably, 1,3-β-glucan exhibits both antiviral and antibacterial activities in humans and substantial antibacterial and immunostimulatory effects in fish [66]. Additionally, sulfated polysaccharides derived from microalgae have been explored for their therapeutic and cosmetic potential, particularly for the treatment of bacterial infections [12]. *Phaeodactylum cruentum* produces a sulfur-containing galactan exopolysaccharide that has been shown to effectively substitute carrageenan in various applications, enhancing its commercial viability. Other microalgal species, such as *Chlamydomonas mexicana*, synthesize approximately 25% of their total organic content as extracellular polysaccharides, further highlighting the versatility of microalgae in producing valuable bioactive compounds [11].

2.4. Vitamins

Vitamins are essential precursors of enzyme cofactors that are critical for metabolic function and exhibit significant antioxidant properties. As humans cannot synthesize most vitamins endogenously, these micronutrients must be acquired through dietary intake [19]. Vitamin deficiencies can lead to a range of health disorders, including beriberi, scurvy, rickets, and methylmalonic acidemia, with potentially severe consequences for overall health [20]. Microalgal biomass is a rich source of nearly all known vitamins, including pro-vitamin A (α- and β-carotene and apocarotenoids), the complete B-vitamin complex (B1 [thiamine], B2 [riboflavin], B3 [nicotinic acid], B5 [pantothenic acid], B6 [pyridoxine], B7 [biotin], and B12 [cobalamin]), vitamin C (ascorbic acid), vitamin D, vitamin E (tocopherols and tocotrienols), and folic acid [19,20]. It is noteworthy that fruits and vegetables are insufficient sources of vitamin B12, as they neither synthesize nor require this essential vitamin [67]. Therefore, microalgal-derived foods are a crucial dietary source of vitamin B12, which is vital for human nutrition. *Dunaliella tertiolecta* has demonstrated the ability to synthesize vitamins B12, B2, E, and A, while *T. suecica* is a notable source of vitamins B1, B3, B5, B6, and C [68]. Furthermore, Watanabe et al. [69] revealed that *Arthrospira* sp. is capable of synthesizing vitamin B12, while *Chlorella* sp. has been shown to provide superior bioavailability of this essential vitamin, which means that vitamin B12 is easily absorbed and effectively used by the body. Merchant et al. [70] found that the daily consumption of 9 g of *C. pyrenoidosa* for 60 days significantly reduced methylmalonic acid (MMA) levels, a marker of vitamin B12 deficiency, by about 34%, indicating its high bioavailability and physiological effectiveness

D. salina is a rich source of β-carotene, a precursor of vitamin A, and can accumulate up to 14% of DW under favorable growth conditions [71]. *Tetraselmis* sp. contains vitamin E (tocopherols) at concentrations ranging from 0.01 to 6.32 mg g^{-1} DW, contributing to its antioxidant potential [71]. Additionally, *Chlorella* sp. and *A. platensis* are remarkable sources of vitamin C (ascorbic acid), with contents ranging from 0.11% to 1.62% DW, which supports immune function and overall well-being [72]. Cyanobacteria, such as *Arthrospira* sp., contain vitamin K1 (phylloquinone) at approximately 200 μg g^{-1}, which is six times higher than the levels found in parsley, a commonly known dietary source of this vitamin [10].

Edelmann et al. [73] reported the vitamin B9 content in *Chlorella* sp. and *Nannochloropsis* sp. powders as 25.9 and 20.8 μg g^{-1}, respectively, suggesting that the consumption of approximately 5 g of these microalgal powders would provide a quarter of the recommended daily intake of 400 μg of vitamin B9. In another study, Tarento et al. [74] found that cyanobacteria contain approximately 200 μg g^{-1} of vitamin K1, which is approximately six times the amount found in parsley (37 μg g^{-1}). Therefore, 1 g of cyanobacteria could

meet the three-times daily requirement for vitamin K1. Moreover, Edelmann et al. [73] highlighted that *Chlorella* sp. contains 2.4 μg g^{-1} of vitamin B12, indicating that 5 g of *Chlorella* powder would supply five times the recommended daily intake of vitamin B12.

Despite these promising findings, there is a notable gap in the research on the bioaccessibility and bioavailability of vitamins derived from microalgae. This underscores the need for further studies to facilitate the incorporation of microalgae into functional food formulations in the regulatory and food industries.

2.5. Pigments

Pigments are secondary metabolites essential for various biological functions, including organism coloration, light energy absorption during photosynthesis, and protection against oxidative stress [18]. These compounds are widely utilized in industries such as food additives, colorants, aquaculture, pharmaceuticals, and nutraceuticals [75]. Currently, pigments are primarily produced from non-renewable synthetic sources, such as petrochemicals, inorganic chemicals, and organic acids, which are often more cost-effective. However, the growing demand for natural pigments is driven by increasing concerns regarding the safety and environmental impact of synthetic alternatives [20,75,76]. In particular, the food industry has shown a clear preference for natural pigments owing to the potential health risks associated with the use of synthetic compounds [76].

Microalgae, including cyanobacteria, have significant potential as sources of natural pigments, producing a diverse range of pigments, such as carotenoids, chlorophyll, and phycobiliproteins, depending on the species. For example, green microalgae are rich in chlorophyll; red and blue microalgae contain phycobiliproteins; and yellow, orange, and red microalgae synthesize carotenoids. Microalgae are considered superior sources of natural pigments because of their ability to synthesize these compounds at higher concentrations than other natural sources [18,20,77].

2.6. Carotenoids

Carotenoids are isoprenoid-structured, lipophilic pigments primarily responsible for the purple, red, orange, and yellow coloration observed in non-photosynthetic organisms, microalgae, and higher plants [17,18]. To date, approximately 600 carotenoids have been identified; however, only β-carotene and astaxanthin have been commercialized for industrial use. Carotenoid compounds, such as lycopene and β-carotene, consist solely of hydrocarbons ($C_{40}H_{56}$), whereas xanthophylls, including lutein, zeaxanthin, and astaxanthin, contain carbon, hydrogen, and oxygen ($C_{40}H_{56}O_2$) [78]. Chlorophyceae, a dominant group of carotenoid-producing microalgae, typically yields approximately 90% xanthophylls and carotenes, with minimal amounts of fucoxanthin, diatoxanthin, and diadinoxanthin [79]. In *C. pyrenoidosa*, a variety of carotenoids have been identified, including cis-lutein isomers, trans-α-carotene, zeaxanthin, α- and β-carotene cis isomers, trans-β-carotene, β-cryptoxanthin, neoxanthin cis isomers, neochrome, auroxanthin, and violaxanthin cis isomers [80]. These carotenoids are known to exhibit significant therapeutic effects in both humans and animals, primarily because of their antioxidant properties, which offer protection against oxidative stress and free radical damage [24]. Furthermore, carotenoids serve as provitamin A precursors, typically representing 0.1–0.2% of the DW of microalgal biomass [81]. The global carotenoid market, valued at USD 2.0 billion in 2022, is projected to grow to USD 2.7 billion by 2027, with a CAGR of 5.7%. Notably, most carotenoid production currently relies on raw chemical materials [82].

β-Carotene is a crucial carotenoid pigment, primarily recognized for its provitamin A activity, which contributes to its widespread use as an additive in multivitamins and as a food colorant [20]. It is predominantly produced by microalgal species such as *Scenedesmus*

almeriensis, *Dunaliella bardawil*, *D. tertiolecta*, and *D. salina* [83]. Among these species, *D. salina* exhibits the highest β-carotene content, accounting for approximately 98.5% of its total carotenoid composition and 10–14% of its biomass DW [24,84]. *Phormidium autumnale* contains 24 distinct carotenoid types, with all-trans-β-carotene, all-trans-lutein, and all-trans-zeaxanthin being the predominant contributors to its biomass [85]. Microalgal β-carotene is particularly abundant in the 9-cis β-carotene isomer, which features a cyclic structure with a cis double bond at positions 9 and 10 [86]. The production of 9-cis isomers can be optimized by adjusting the culture medium conditions, thus enhancing the yield [23]. Notably, the 9-cis isomer of β-carotene has been shown to exert beneficial effects on plasma lipid profiles, potentially contributing to the prevention of atherosclerosis in humans [87]. Previous studies have demonstrated that adequate intake of β-carotene, in conjunction with other antioxidants, may reduce the risk of atherosclerotic diseases, particularly in the presence of risk factors such as smoking, hypertension, dyslipidemia, and diabetes [88].

2.7. Astaxanthin

Astaxanthin, a red xanthophyll carotenoid, is recognized as a potent natural antioxidant that exhibits antioxidant properties up to 100 times more powerful than those of vitamin C and 10 times more potent than those of other carotenoids, such as β-carotene, lutein, lycopene, and zeaxanthin [18,20,89]. It is the second most significant carotenoid pigment, predominantly extracted from the freshwater green microalga *Haematococcus pluvialis*, which contributes to approximately 81% of the total carotenoid yield (7% DW) [90]. Currently, the aquaculture industry extensively utilizes astaxanthin-rich microalgae as feed ingredients for fish and crustaceans [91]. Other microalgal species, including *Chlorella zofingiensis*, *Chlorococcum* sp., and *Scenedesmus* sp., also produce astaxanthin, albeit at lower concentrations [18]. Recent studies have highlighted the potential of astaxanthin to reduce inflammation and oxidative stress while enhancing the immune response, particularly in patients with cardiovascular diseases [20,92]. For instance, Kim et al. [92] demonstrated that the consumption of astaxanthin derived from *H. pluvialis* mitigated oxidative damage in heavy smokers by suppressing lipid peroxidation. Additionally, Yoshida et al. [93] reported that daily consumption of 12–18 mg of natural astaxanthin significantly increased serum high-density lipoprotein (HDL) and adiponectin levels in non-obese individuals.

2.8. Chlorophyll

Chlorophyll, a natural green pigment, is synthesized by photoautotrophic microalgal species, such as chlorophyll a, b (in green algae), and c (in brown algae), to harness solar energy for photosynthesis. The chlorophyll content in microalgal cells typically ranges from 0.5% to 4% of the total DW biomass, with variations depending on the strain and growth conditions [20]. *Chlorella* sp. is a predominant producer of chlorophyll, while *Arthrospira* sp. yields lower concentrations of this pigment [83]. Beyond its role in photosynthesis, chlorophyll is recognized for its potent antioxidant activity and exhibits a range of therapeutic properties, including anticarcinogenic, antigenotoxic, and antimutagenic effects [94]. Chlorophyll consumption has been shown to enhance bile secretion and facilitate liver recovery [95]. Furthermore, chlorophyll is acknowledged as a detoxifying agent and phytonutrient that contributes positively to human reproduction and the regulation of protein, carbohydrate, and lipid metabolism [96]. Chlorophyll also contains water-soluble chlorophyllin, which exhibits cancer-preventive properties by targeting multiple carcinogenic pathways and disrupting the cell cycle [97].

2.9. Phycobiliproteins

Phycobiliproteins are hydrophilic protein complexes that play a pivotal role in light energy capture and photosynthesis in cyanobacteria (e.g., *Arthrospira* sp.), red microalgae (e.g., *Porphyridium* and *Galdieria*), cryptophytes, and glaucophytes [98,99]. These proteins are classified into four categories based on their specific light absorption spectra: phycoerythrins (540–570 nm), phycocyanins (610–620 nm), allophycocyanins (630–650 nm), and phycoerythrocyanins (560–600 nm) [100]. Phycocyanin, a fluorescent blue phycobiliprotein, is commonly extracted from *Arthrospira* sp. and used as a natural colorant in various food products, including frozen confections, chewing gum, confectioneries, wasabi, dairy products, and carbonated beverages. In the nutraceutical industry, these pigments have been promoted for their potential anti-inflammatory, antioxidative, antiviral, hepatoprotective, and neuroprotective properties [94,101,102].

3. Application of Microalgae in the Food Industry

3.1. Functional Foods and Nutraceuticals

The incorporation of microalgal biomass into functional foods enhances their functional properties, owing to their high protein content and the presence of valuable bioactive components, such as pigments and PUFAs [18,103–105], amino acids, mineral salts, and vitamins [10]. Microalgal biomass can be consumed as a functional food, similar to conventional foods, or as nutraceuticals in the form of dietary supplements, such as powders, capsules, pills, and tablets [20,103]. The integration of microalgae into conventional food products can significantly improve their nutritional profile while preserving essential textural properties, including firmness and fracturability, without altering their taste [12,106]. However, certain microalgal species may impart undesirable odors (e.g., fishy aroma) or exhibit bright green coloration, which could negatively affect consumer acceptance [24]. Additionally, the nutritional composition of fresh microalgal biomass is highly susceptible to changes induced by various processing methods, such as heat drying, light exposure during storage, grinding, and packaging [32]. Addressing these limitations through the development of eco-innovative processing techniques will facilitate the broader application of microalgal-based ingredients in the competitive functional food market [18].

3.2. Microalgae-Enriched Foods and Their Health Benefits

Microalgal species such as *Arthrospira* sp., *Chlorella* sp., *Chlamydomonas* sp., *Dunaliella* sp., *Euglena gracilis*, *Haematococcus* sp., *Schizochytrium* sp., *P. cruentum*, *C. cohnii*, and *Ulkenia* sp. have been classified as GRAS by the regulatory authorities, and have been successfully commercialized across a range of biotechnological sectors, including functional foods, dietary supplements, food additives, animal feed and fodder, agricultural ingredients, pharmaceuticals, personal care products, and dyes [23,27,94,107] (Table 3).

The food industry utilizes both whole microalgal biomass and extracted biocomponents as ingredients in a range of food products, including pasta, bread, noodles, desserts, cookies, cheese, and yogurt, to enhance their nutritional properties [108–114]. These microalgae-enriched foods have demonstrated potential health benefits, such as reducing serum cholesterol levels, lowering the risk of cardiovascular diseases, improving diabetes symptoms, decreasing blood pressure, preventing cancer, and enhancing gastric health and nutrient absorption [26,51,59] (Figure 1). For example, the addition of microalgal powders to conventional food products rich in proteins, amino acids, and mineral salts holds promise as a protein supplement. Moreover, when processed into a paste, microalgal biomass retains its high nutritional value, further solidifying its role in the functional food market [115].

Table 3. Commercialization of some major microalgal species for various applications.

Commercial Industry	Microalgae Species	Area of Application	Location
Algae Tech.	-	Nutraceuticals, animal feed, and aquafeed	Seaford, VIC, Australia
Algomed	*Chlorella* sp. and *Arthrospira* sp.	Food supplements and nutraceuticals	Klötze, Germany
AlgoSource	*Arthrospira maxima*, *Arthrospira platensis*, *Scenedesmus* sp.	Nutraceuticals, cosmetics, and health	Guérande, France
Algatechnologies Ltd.	*Haematococcus pluvialis*, *Phaeodactylum tricornutum*, *Porphyridium cruentum*, and *Nannochloropsis* sp.	Nutrition, food and beverages, and cosmetics	Ketura, Israel
Aurora Algae Inc.	-	Pharmaceutical, nutrition, aquafeed, and fuels	Hayward, CA, USA
Allmicroalgae	*Chlorella vulgaris*, *A. platensis*, *Tetraselmis* chui, *Nannochloropsis oceanica*, *Scenedesmus rubescens*, *P. tricornutum*, and *Chlorococcum amblystomatis*	Dietary supplements, food, feed, and agro applications	Pataias, Portugal
BlueBioTech International GmbH	*A. platensis* and *H. pluvialis*	Nutraceuticals	Kollmar, Germany
Cyanotech Corporation	*H. pluvialis* and *Arthrospira* sp.	Functional foods	Kailua-Kona, HI, USA
Canadian Pacific Algae, Inc.	Marine phytoplankton	Functional foods and nutraceuticals	Nanaimo, BC, Canada
Parry nutraceuticals	*Arthrospira* sp., *Chlorella* sp., *Dunaliella salina*, and *H. pluvialis*	Astaxanthin, food supplements, and nutraceuticals	Tamil Nadu, India
Euglena Co., Ltd.	*Euglena gracilis*, *Euglena mutabilis*, *Euglena sanguinea*, and *Euglena agilis*	Nutritional supplements, biofuels, feed, fertilizers, and biomass plastics	Minato City, Japan
Fermentalg SA	-	Omega 3 fatty acids, coloring agents, antioxidants, and biopolymers	Libourne, France
Oilgae	-	Food, feed, nutraceuticals, pharmaceuticals, biofuel, biopolymers, cosmetics, paper, lubricants, and chemicals	Chennai, India
Sun *Chlorella* A	*Chlorella* spp.	Nutritional supplements, food, feed, and personal care	Kyoto, Japan
Subitec	*Anabena* sp., *Aphanizomenon Flos-Aquae*, *C. vulgaris*, *Cyanobacterium aponinum*, *D. salina*, *H. pluvialis*, *Nannochloropsis* sp., *P. tricornutum*, *Scenedesmus* sp., *A. platensis*	Food supplements, pharmaceutical, personal care, and animal feed	Köngen, Germany
Simris Alg. AB	Cyanobacterial species	Food supplements, nutraceuticals, and skin care	Hammenhog, Sweden
Solarvest BioEnergy Inc.	-	Nutraceuticals	Vancouver, BC, Canada
Mera Pharmaceuticals	-	Personal care and food supplements	Las Vegas, NV, USA
ZIVO Bioscience, Inc.	-	Food supplements	Bloomfield Hills, MI, USA
Taiwan *Chlorella* Manufacturing	*Chlorella* spp.	Algae-based foods (juice, noodles, and chocolates) and nutritional supplements	Taipei City, Taiwan

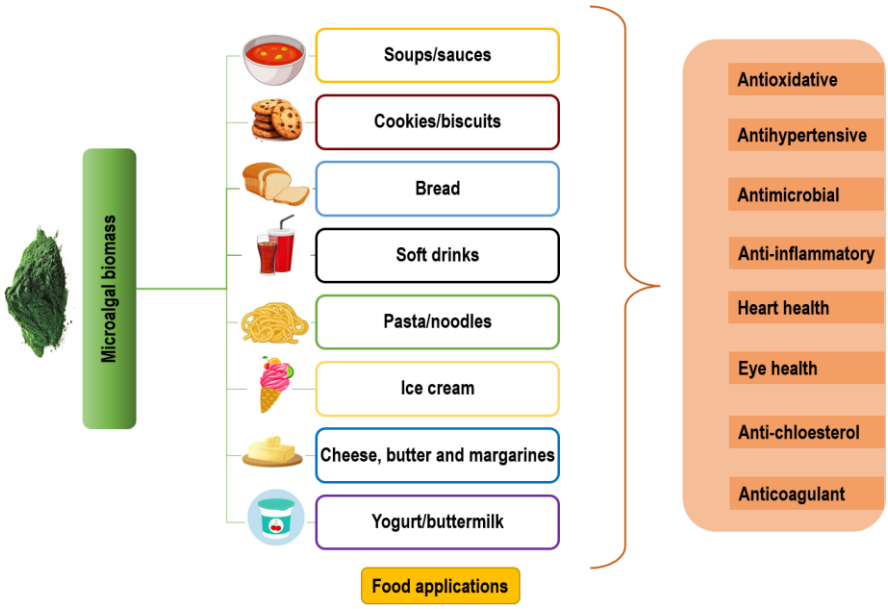


Figure 1. Schematic overview of the health advantages of microalgae and their possible use as food sources.

Batista et al. [116] conducted a study to enhance the nutritional profile and health benefits of cookies by incorporating microalgae, including *A. platensis*, *C. vulgaris*, *T. suecica*, and *P. tricornutum*, which resulted in a significant increase in the protein and antioxidant levels. Similarly, *Dunaliella* sp. was identified in a previous study as a potential protein supplement for white bread [117]. Additionally, *A. platensis* and its decolorized extracts have been successfully integrated into bread to enhance its protein content [118]. Recent investigations have further demonstrated that the inclusion of microalgae in gluten-free bread formulations, particularly *Arthrospira* sp., not only elevates the protein content but also improves the bread quality by contributing essential amino acids (EAAs) [119]. Nevertheless, it is important to highlight that increased consumption of microalgal proteins may lead to gastrointestinal discomfort and indigestion, primarily due to their high nucleic acid and fiber contents [108]. Regulatory bodies such as the FDA and EFSA suggest a daily protein intake of up to 0.8 g kg^{-1} body weight. However, no specific RDI values for microalgal protein consumption have been established [11]. It is recommended to incorporate microalgal proteins into the overall daily intake, following the general protein consumption guidelines.

P. lutheri is often included in yogurt formulations due to its anti-inflammatory properties and omega-3 content [120]. *Schizochytrium* sp., renowned for its high DHA content, has attracted significant attention as a valuable source of DHA-rich oil [121]. Furthermore, the consumption of DHA from *Ulkenia* sp. has been shown to significantly increase omega-3 accumulation in red blood cells, thereby influencing appetite regulation and food intake. Health beverages, such as infant-grade milk and *Chlorella*-fortified drinks, are often enriched with omega-3 fatty acids (EPA, DHA, and ALA) to support optimal health [122]. EPA has demonstrated considerable potential for treating coronary heart disease (CHD) and preventing thrombosis and atherosclerosis [11]. It is commonly incorporated into various bakery products, including cookies, fillings, pastries, frostings, and toppings. Additionally, algae-based butter spreads offer a source of beneficial fats while imparting desirable qualities, such as gloss, a natural appearance, rapid melting, and a clean taste. The incorporation of algae-based butter into confectionery products has been shown to be compatible with cocoa butter, enhancing its stability, fat content, and overall sensory properties of the product [51,123].

Microalgae-derived exopolysaccharides play a crucial role in supporting bacterial growth and exhibit probiotic properties. *A. platensis* and *Chlorella* sp. have been successfully incorporated into dairy products, such as yogurt, to enhance the functionality by improving nutritional composition, providing antioxidant properties, supporting gut health, and promoting the viability of probiotic microorganisms (*Lactobacillus acidophilus* and *Bifidobacterium lactis*) [124]. The integration of microalgae into bakery products, such as cookies, has been shown to improve their organoleptic properties, versatility, and consumer appeal. For example, incorporating *C. vulgaris* into cookie formulations enhanced firmness and resulted in a greenish coloration [125]. Despite these promising applications, microalgal starch is not commonly used as a substitute for terrestrial plant-derived starches [126]. Floridian starch, known for its low gelatinization and pasting temperatures, is extensively used in the production of instant noodles and frozen foods [127]. Differential scanning calorimetry and rapid viscosity analysis have demonstrated that microalgal polysaccharides exhibit low gelatinization temperatures, favorable viscosity, high clarity, and minimal retrogradation during freeze–thaw cycles. Furthermore, chrysolaminarin, a well-established antioxidant, has been explored as a dietary component and effective drug delivery agent for the development of biomaterials [128]. In addition to its antioxidant properties, paramylon has shown significant efficacy in alleviating carbon tetrachloride-induced liver oxidative damage [129].

Polysaccharides and oligosaccharides derived from microalgae have garnered significant attention owing to their potential health benefits, particularly in prebiotic applications. Prebiotics are indigestible food components that specifically enhance the growth and function of beneficial bacteria in the large intestine, thereby improving gut health. Because of their high carbohydrate and oligosaccharide content, various microalgal species, including *Arthrospira*, *Chlorella*, and *Nannochloropsis*, have been extensively studied for their prebiotic potential [106]. For instance, polysaccharides from *A. platensis* promote the growth of *Lactobacillus* and *Bifidobacterium* species, which contribute to a healthier gut microbiome and improved digestion [130]. Similarly, oligosaccharides from *C. vulgaris* act as fermentable substrates for gut microbes, leading to the production of short-chain fatty acids (SCFAs), which help maintain colon health and regulate lipid metabolism [131]. Furthermore, *D. salina* polysaccharides exhibit antiviral and anticancer properties, whereas *H. pluvialis*-derived oligosaccharides exhibit anti-inflammatory effects. Additionally, *P. tricornutum* polysaccharides exhibit antihypertensive properties, contributing to cardiovascular health [132].

3.3. Challenges in Processing and Consumer Acceptance

The consumption of functional foods incorporating microalgal ingredients for health benefits has been steadily increasing. However, variations in the nutrient composition of microalgae have been observed across studies, with potential factors including geographical origin, harvest timing, culture medium characteristics, genetic variability, harvesting conditions, and extraction methods, particularly the solvents employed [133]. Furthermore, both intrinsic and extrinsic properties of functional foods, such as pH, fat content, protein composition, water content, and oxygen concentration, underscore the need for further mechanistic investigations, particularly regarding preservation techniques. Significant research and development efforts have been directed toward overcoming the technical challenges in extraction processes to meet the market specifications for final food products. Microalgae-derived additives can be incorporated into a wide range of products, including liquids for beverages, powders for flour-based products, oils for fatty foods, and tablets or capsules for dietary supplements [104].

3.4. Consumer Trends and Innovations in Microalgae-Based Foods

Modern consumers' increasingly hectic lifestyles are driving the demand for affordable, convenient, and nutritious food options. Moreover, consumers are increasingly drawn to plant-based and environmentally friendly food sources, and microalgae are well aligned with this trend [134,135]. Snacks enriched with *A. platensis* have demonstrated enhanced protein, minerals, and lipids while maintaining a desirable texture, flavor, and taste, achieving an impressive 82% sensory acceptability [136]. Similarly, bread formulated with *C. vulgaris* and *A. platensis* exhibited enhanced iron and selenium content while retaining color and texture stability for over 15 days [137]. In dairy products, cheese spreads fortified with *C. vulgaris* showed higher concentrations of magnesium (Mg), potassium (K), selenium (Se), zinc (Zn), iron (Fe), and antioxidant potential [138].

In addition to solid foods, microalgae have been successfully incorporated into functional beverages and dairy alternatives. Yogurt enriched with omega-3-rich microalgal oil from *Schizochytrium* sp. provided a higher bioavailability of n-3 PUFAs than non-enriched variants, demonstrating the potential of microalgal-derived lipids to enhance dietary omega-3 intake [139]. Additionally, broccoli soups supplemented with *Arthrospira* sp., *Chlorella* sp., and *Tetraselmis* sp. exhibited increased antioxidant capacity and bioaccessible polyphenols, enhancing the functional and health-promoting properties of microalgal ingredients [140].

Researchers have successfully developed bread enriched with *Arthrospira* sp. and other microalgae, enhancing its protein content, mineral availability, and overall nutritional value [141]. Although the addition of microalgae alters the color and taste profiles of the products, consumer feedback has generally been positive, with many consumers appreciating the unique flavor and associated health benefits [142]. Recent innovations have led to the development of microalgae-fortified muffins, grissini, and crackers, which provide higher protein content and increased antioxidant activity. These microalgae-enriched snacks maintain a texture similar to that of traditional snacks, with a distinctive green hue characteristic of microalgal ingredients [142]. A notable breakthrough in microalgae-based foods is the formulation of vegan ice cream derived from *Chlorella* sp. biomass. This nutrient-dense alternative to traditional ice cream provides high levels of vitamin B12, iron, and essential micronutrients, making it an ideal choice for vegan consumers. Additionally, this product addresses the sustainability concerns associated with dairy production, supporting the shift towards plant-based alternatives [139].

Recent innovations have expanded the application of microalgae in baked goods, snacks, beverages, and plant-based protein alternatives for humans. Studies have demonstrated that bread and pasta enriched with *Arthrospira* sp. and *Nannochloropsis* sp. enhance nutritional density and contribute to better sensory acceptability and stability [142]. The development of microalgae-based meat substitutes, functional sports nutrition products, and dairy alternatives is further driving market expansion, catering to health-conscious and environmentally aware consumers [143]. Furthermore, the formulation of microalgae-fortified functional foods has gained interest because of their ability to improve gut health, cardiovascular function, and cognitive performance, making them a key emerging trend in the nutraceutical industry.

These advancements highlight the need for comprehensive formulation strategies that ensure the effective incorporation of microalgal ingredients into commercial food products while maintaining their taste, texture, and stability. Future research should focus on optimizing processing methods to enhance the bioavailability, palatability, and consumer acceptance of microalgae-based foods in the global market [134,142].

4. Consumer Acceptance, Sustainability Issues, and Safety Concerns in Microalgae

4.1. Consumer Acceptance of Microalgae-Based Foods

Although microalgal technology offers numerous potential benefits, consumer acceptance of microalgae in diets remains uncertain. Algal-based foods are well established in certain regions, particularly in East Asian countries such as Japan, Korea, and China [144]. In contrast, their prevalence is relatively low in many Western countries, where they are often found in foreign cuisines or marketed as premium health products [145]. Despite some skepticism regarding the sensory attributes of microalgae, Western consumers generally exhibit a willingness to consume functional foods, particularly when these products are framed in terms of their health benefits, nutritional value, and innovation [144]. While the acceptance of seaweed (macroalgae) has been well documented, research on microalgae acceptance is emerging, particularly in Europe. European consumers are largely unfamiliar with microalgae and have not widely embraced them [146]. However, individuals aware of the potential health benefits of microalgae consumption are more likely to express positive intentions toward future consumption, especially regarding sustainability, health benefits, nutritional value, and safety [146,147]. Despite this, consumers remain hesitant to compromise on taste or pay a premium for eco-friendly or nutrient-dense products [148].

Few studies have specifically investigated consumer acceptance of microalgae as an alternative to meat protein. However, research conducted in the European Union suggests a preference for microalgae over processed meat, although there is less enthusiasm for algae-based products such as burgers and jerky [144]. This reluctance to replace conventional meat with alternative proteins may be attributed to the strong cultural attachment to meat and the perception that meat is more palatable, convenient to prepare, nutritious, affordable, and natural than alternatives [149,150]. Additionally, certain sensory factors, such as taste, texture, bright green color, and fishy odor associated with microalgal biomass, may pose challenges to consumer acceptance [94]. These attributes are critical for the development of microalgae-based food products and ingredients.

4.2. Antinutritional Factors in Microalgae

Despite their significant nutritional value, microalgae may also contain anti-nutritional factors that can influence nutrient absorption and metabolism. The common antinutritional compounds present in microalgae include phytic acid, tannins, oxalates, and nucleic acids, which can limit the bioavailability of essential minerals, such as iron, calcium, and zinc. For instance, *A. maxima* and *C. vulgaris* have been reported to contain tannic acid levels of 6.86 mg g^{-1} and 1.44 mg g^{-1}, respectively, which, when consumed in excess, may interfere with protein digestibility and mineral absorption [151]. Moreover, the high nucleic acid content in microalgae, which metabolizes into uric acid, may lead to potential health issues such as gout or kidney stones [152]. To mitigate the impact of these antinutritional factors, several pretreatment techniques, such as fermentation, enzymatic hydrolysis, and thermal processing, have been investigated [153]. Studies have shown that fermentation using microalgal strains such as *Aspergillus sojae* and *Aspergillus ficuum* has been shown to significantly reduce the concentrations of phytic acid and tannins, thereby enhancing the nutritional bioavailability of microalgal biomass [151]. Furthermore, the cell disruption techniques improve the bioavailability of microalgae such as *C. vulgaris*, *N. oceanica*, and *P. tricornutum*, which enhances the nutrient absorption during consumption [154].

4.3. Sustainability and Market Potential of Microalgae

Microalgae are increasingly recognized not only for their nutritional value but also for their additional benefits, positioning them as key ingredients in “functional foods” and

"nutraceuticals." Although the market share of microalgae-based products remains smaller than that of the broader food and feed sectors, the production of microalgal biomass has increased fivefold since 2000 [27]. These algae-based products, which include vitamins, carotenoids, PUFAs, proteins, and phycocyanin, are gaining attention in the food and beverage, pharmaceutical, cosmetics and personal care, aquaculture and animal feed, and biofuel industries. The market for algae-based products is categorized by product type, value, volume, and application, spanning nutraceuticals, personal care, agriculture, food, and animal feed. Currently, the global microalgal products market is valued at approximately US $4.96 billion and is projected to expand at a CAGR of 4.8–9.1 billion by 2032 [16].

Natural or artificial ponds are commonly employed for microalgal biomass production for various biotechnological applications, including bioremediation [86], biofuel production (biodiesel, bioethanol, biohydrogen, and biogas) [155], nutraceuticals [94], functional foods [144], pharmaceuticals [145], and cosmetics [15]. However, environmental factors, such as light intensity, pH, dissolved oxygen levels, and temperature, can significantly influence growth rates in open systems. Therefore, the future of microalgal biotechnology hinges on the development of large-scale photobioreactors that can provide optimal growth conditions while minimizing contamination risks [94]. Cultivating microalgal biomass on a large scale is resource-intensive and requires significant time, labor, and expensive equipment. Consequently, microalgal biomass production is more expensive than other feedstocks, with recovery expenses accounting for 20–30% of the total production cost [107,156].

Recent advancements in microalgal processing and optimization of cultivation and harvesting systems are critical for improving the feasibility and profitability of large-scale microalgal production. Innovations in cost-effective cultivation techniques, such as optimizing culture media with fertilizers and urea supplements, have enhanced biomass productivity and increased the yield of valuable compounds, such as lutein, while substantially reducing the production costs [157]. Additionally, the development of advanced photobioreactors, including tubular, flat-panel, and bubble column systems, has optimized growth conditions, leading to higher biomass yields and efficient cultivation processes [57,157]. Purified microalgal derivatives, such as omega fatty acids, antioxidants, and colorants, generate significantly higher revenues than unrefined whole biomass [107]. Currently, the global market for microalgal biomass produces approximately 5000 metric tons annually, with production costs averaging $25,000 ton^{-1}. *Arthrospira* sp. dominates the market, accounting for 12,000 tons of biomass year^{-1}, nearly 70% of which is produced in Asia. Other significant contributors include *Chlorella* (5, 000 tons year^{-1}), *D. salina* (3000 tons of carotene), *Aphanizomenon flos-aquae* (1500 tons of food), *H. pluvialis* (700 tons of astaxanthin), *C. cohnii* (500 tons of DHA), and *Schizochytrium* sp. (20 tons of DHA) [27,94].

4.4. Regulatory and Safety Concerns

Food safety remains a critical concern for regulatory agencies in developed regions, including Australia, Canada, the United States, New Zealand, and the European Union. In the United States, the FDA classifies microalgal-based food products as GRAS under the Center for Food Safety and Applied Nutrition (CFSAN). Microalgal species such as *Arthrospira*, *Chlorella*, *Dunaliella*, *Haematococcus*, and *Schizochytrium* have achieved GRAS status, facilitating their incorporation into various food products [19].

In the European Union, several microalgal products have been approved under the regulations of the Regulation on Food Safety and the Regulation on Novel Food and Novel Food Ingredients (EU) No. 2015/2283 [26]. These regulatory frameworks aim to streamline the authorization process, facilitate the market entry of safe and innovative food products, and reduce trade barriers, while ensuring that high food safety standards are upheld [94].

Species such as *A. platensis*, *Chlorella luteoviridis*, *C. pyrenoidosa*, and *C. vulgaris* are exempt from this regulation because of their established history of consumption. In contrast, species such as *Tetraselmis chuii* and *Schizochytrium* sp. have been authorized as novel foods, reflecting the EU's commitment to consumer safety through rigorous evaluation [158,159].

Australia and New Zealand regulate novel foods through Food Standards Australia New Zealand (FSANZ), which requires a comprehensive safety assessment prior to market approval of the product. The use of DHA-rich oil derived from Schizochytrium sp. has been authorized as a novel food ingredient, exemplifying the region's cautious approach to introducing novel foods [160]. In Canada, novel foods, including certain microalgal products, require a pre-market safety assessment by Health Canada. The regulatory body advises caution regarding cyanobacterial products not derived from *Arthrospira* sp., underscoring the importance of species-specific evaluations to ensure consumer safety [160].

Despite the promising applications of microalgae, safety concerns regarding heavy metal contamination have emerged as significant issues. Microalgae can accumulate toxic heavy metals, such as cadmium (Cd), lead (Pb), mercury (Hg), and arsenic (As), depending on their concentration in the surrounding environment [26]. While this characteristic makes microalgae effective for environmental remediation, it also raises concerns about the safety of algae-based food and feed products. Studies have shown that microalgal species, such as *A. platensis* and *C. vulgaris*, can accumulate high levels of metals from contaminated water, which can pose potential health risks if these metals are present in significant quantities in the final products [161]. In particular, excessive accumulation of metals such as copper (Cu), nickel (Ni), and zinc (Zn) can lead to oxidative stress, which affects the quality and safety of microalgae-based products intended for human consumption [162].

Several strategies have been proposed to mitigate these risks. Optimizing cultivation conditions, such as controlling pH, light intensity, and nutrient concentration, can help reduce metal uptake by microalgae, thereby enhancing product safety [161]. Furthermore, the selective breeding of microalgal strains with reduced metal accumulation and pretreatment methods, such as washing or chemical treatments, can effectively reduce heavy metal content in microalgal biomass [163]. Recent analyses have shown that the regulatory limits for heavy metals, pesticides, and mycotoxins are being met for commercially cultivated strains such as *Arthrospira* and *Chlorella* [157]. However, concerns persist regarding the levels of polycyclic aromatic hydrocarbons (PAHs), which exceed acceptable limits in some commercial strains, underscoring the need for rigorous monitoring to ensure consumer safety in the future.

5. Future Prospects

A comprehensive review of the existing scientific literature underscores the growing use of microalgae as a renewable resource for producing bioactive compounds, particularly in the food industry. However, it is essential to ensure the safety and quality of microalgal biomass and its derivatives in accordance with FDA regulations and other relevant safety standards. Several key concerns must be addressed to facilitate the safe production and consumption of microalgal-based products: (1) certain microalgal species, including cyanobacteria and dinoflagellates, have been shown to produce hepatotoxic and neurotoxic compounds, which pose significant health risks; (2) the high nucleic acid content in microalgal biomass, which is metabolized to uric acid, may contribute to conditions such as gout and kidney stones, necessitating careful intake monitoring; (3) sensory characteristics, including taste, texture, color, and odor, often limit the widespread use of microalgae-based foods, thus research is needed to determine optimal microalgal concentrations and integration strategies to enhance product palatability and consumer acceptance without compromising nutritional value; (4) the production and processing of microalgae must be

carefully controlled to identify and mitigate potential hazards throughout the entire supply chain, from cultivation to packaging, ensuring the safe inclusion of microalgal ingredients in food products; (5) although the health benefits of microalgae are well documented, studies indicate that certain microalgae-based products may trigger allergic reactions in sensitive individuals, possibly due to genetic variability.

6. Conclusions

Microalgae are a sustainable source of bioactive compounds with potential applications in the food, nutraceutical, and pharmaceutical industries. The integration of microalgae into food systems requires careful assessment of safety, quality, and consumer acceptance. Key challenges remain, including the potential presence of toxic compounds in certain microalgal species, the impact of high nucleic acid content on human health, and sensory limitations that inhibit widespread adoption. Future research should develop optimized cultivation and processing techniques to overcome these challenges while ensuring regulatory compliance and safeguarding consumer health. Additionally, exploring the sensory modifications required to improve taste, texture, and color will be critical for enhancing the commercial viability of microalgae-based products. With continued advancements in biotechnology coupled with growing consumer awareness of sustainability and functional foods, microalgae hold promise as a cornerstone of the future food industry, providing innovative solutions to global nutritional challenges. Ultimately, the successful integration of microalgal biomass into food products depends on a multidisciplinary approach that combines technological innovation, regulatory oversight, and consumer-driven research to unlock the full potential of these organisms.

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