

<http://foodbulletin.net>

e-ISSN: 2979-9848

<https://prensip.gen.tr>

REVIEW ARTICLE

Sustainable Food Ingredients: Micro-Algae as Source Bioactive Compounds

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ARTICLE INFO

Article History

Received: 27.11.2024

Accepted: 26.12.2024

First Published: 30.12.2024

Keywords

Bioactive compounds

Food sustainability

Functional additives

Micro-algae

Sustainable ingredients

ABSTRACT

Microalgae hold immense promise as a sustainable, bioactive source of functional food additives, presenting a unique profile of polyunsaturated fatty acids (PUFAs), carotenoids, vitamins, peptides, and polysaccharides with notable health benefits. Known for their ability to produce compounds like astaxanthin and lutein, *Haematococcus pluvialis*, *Chlorella zofingiensis*, and *Spirulina* contribute to antioxidant, anti-inflammatory, cardiovascular, and visual health when incorporated into food products. Unlike traditional crops, microalgae cultivation requires fewer resources (minimizing land, water, and carbon footprint) while achieving higher photosynthetic efficiency, making them a sustainable solution well-aligned with modern food production goals. However, despite their potential, the mainstream adoption of microalgae-derived bioactives is limited by challenges such as high production costs, complex extraction processes, and stringent regulatory barriers, particularly in markets like the EU. To address these limitations, advancements in photobioreactor technology, biorefinery approaches, and genetic engineering have shown promise in enhancing yield and reducing costs, thereby positioning microalgae as economically viable alternatives to synthetic additives. Furthermore, innovations in encapsulation and bioavailability improvement are advancing, making microalgal compounds more effective and stable in various food systems. This article explores the significant role microalgae could play in food sustainability, reviewing recent research and industry insights to propose practical solutions that encourage broader integration of microalgal bioactives in global markets. Through strategic technological improvements and supportive policy frameworks, the food industry could embrace microalgae-derived compounds, paving the way for resilient food systems that address consumer demands for natural, health-promoting ingredients. With ongoing academic and industrial collaboration, microalgae's high nutritional value and environmental benefits can be leveraged to support both human health and ecological sustainability, signifying their crucial place in future food innovation.

**Please cite this paper as follows:**

Baldemir, P., & Çaklı, Ş. (2024). Sustainable food ingredients: Micro-algae as source bioactive compounds. *Food Bulletin*, 3(2), 34-40. <https://doi.org/10.61326/foodb.v3i2.315>

1. Introduction

Micro-algae are increasingly attracting attention due to their superior nutrient profiles and environmentally sustainable cultivation methods. Microalgae can produce a variety of bioactive compounds and their photosynthetic efficiency is significantly higher than that of land plants, including carotenoids, polyunsaturated fatty acids (PUFAs), proteins and

polysaccharides (Ambati et al., 2014). With these characteristics, microalgae stand out as a viable solution to address the global need for sustainable, healthy food additives by both meeting nutritional needs and minimizing environmental concerns.

The cultivation of microalgae is resource efficient as it requires significantly less water and arable land than

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conventional crops. This strengthens their role in sustainable food systems (Bernaerts et al., 2018; Caporgno & Mathys, 2018). Of particular interest is the production of astaxanthin, an antioxidant derived from *Haematococcus pluvialis*, with applications in dietary supplements, cosmetics and functional foods. Reflecting growing consumer demand for natural bioactives, the global astaxanthin market is estimated to exceed \$2.57 billion by 2025 (Pan-utai et al., 2021). Likewise, species such as *Chlorella* are recognized for their rich composition of essential fatty acids, pigments, and albumen, which makes it ideal for enhancing the functional and nutritional properties of foods (Caporgno & Mathys, 2018).

Despite their potential, several challenges hinder the mainstream adoption of microalgae in the food industry. The high cost of production, the technical complexity associated with the extraction of biomass, and the regulatory restrictions, especially in the European Union, are significant barriers (Bernaerts et al., 2018). Advances in biorefinery processes and genetic engineering offer promising solutions by increasing yields and reducing costs, enabling microalgae to become seamlessly integrated into global food systems (Ambati et al., 2014). Furthermore, the urgency to adopt natural and sustainable alternatives is underscored by the shift away from synthetic food additives as consumers prefer clean-label products.

In this review, we focus on primary and secondary metabolites, production challenges, and commercialization strategies to critically assess the bioactive potential of microalgae. A synthesis of recent academic and industrial knowledge is provided to identify ways to scale up the use of microalgae as sustainable food ingredients.

2. High-Value Microalgae Primary Metabolites

2.1. Polyunsaturated Fatty Acids (PUFAs)

Microalgae are a sustainable and efficient source of polyunsaturated fatty acids (PUFAs), including docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA). These fatty acids are important for cardiovascular health, neural development, and inflammation regulation. In contrast to traditional sources of fish oil, the cultivation of microalgae addresses environmental issues such as overfishing and greenhouse gas emissions, providing an environmentally friendly alternative. Some strains, such as *Cryptocodinium cohnii* and *Phaeodactylum tricorutum*, are especially notable for their high levels of DHA and EPA, accounting for 60% and 30 to 40% of their respective lipid profile (Mendes et al., 2009; Qiao et al., 2016). In a similar way, *Schizochytrium sp.* has been recognized for its ability to accumulate DHA to a level of more than 50% of its lipid composition, which makes it highly suitable for applications in functional foods and nutraceuticals (Torres-Tiji et al., 2020).

Advances in cultivation techniques have also enhanced the production of lipid-rich biomass. For instance, *Auxenochlorella protothecoides* achieves lipid contents of up to 70% of its dry weight under optimized conditions, supporting scalable production of omega-3 fatty acids (Patel, et al., 2018). The health benefits of microalgal PUFAs are extensive, ranging from reducing systemic inflammation to improving lipid profiles and supporting cognitive health (Caporgno & Mathys, 2018). These qualities have driven their incorporation into diverse consumer products, including infant formulas, dietary supplements, and functional beverages.

The unique ability of microalgae to provide a sustainable source of bioavailable omega-3 fatty acids underscores their transformative potential within the global food industry. As demand for plant-based alternatives continues to rise, microalgae-derived PUFAs present a compelling solution that bridges the gap between environmental sustainability and human health.

2.2. Polysaccharides

Polysaccharides derived from microalgae exhibit diverse functional and bioactive properties, rendering them invaluable in both the food and pharmaceutical industries. These structural carbohydrates are renowned for their immunomodulatory, anti-inflammatory, antiviral, and cytotoxic effects, which position them as both therapeutic agents and functional food components (Challouf et al., 2011; Jo et al., 2010). For example, sulphated polysaccharides from *Tetraselmis suecica* are effective in inhibiting inflammatory mediators such as nitric oxide (NO), interleukin-6 (IL-6) and tumor necrosis factor-alpha (TNF-alpha), demonstrating their potential in the treatment of inflammatory diseases (Jo et al., 2010). Additionally, polysaccharides from *Arthrospira platensis* demonstrate cytotoxicity against colon and kidney cancer cells, underscoring their potential applications in oncology (Challouf et al., 2011).

Certain species, such as *Navicula directa*, produce antiviral polysaccharides effective against influenza and herpes simplex viruses, broadening their utility in combating viral infections (Lee et al., 2006). Beyond therapeutic applications, polysaccharides from *Porphyridium cruentum* and *Chlorella stigmatophora* are notable for their antioxidant and immune-enhancing properties, which make them attractive as natural additives in functional foods (Bernaerts et al., 2018; Mtaki et al., 2020). These bioactive compounds also function as natural thickeners or stabilizers, offering clean-label alternatives to synthetic food additives while enhancing texture and shelf life (Ambati et al., 2014).

Innovative extraction techniques, such as ultrasound-assisted methods, have improved the accessibility and cost-efficiency of microalgal polysaccharides, paving the way for their incorporation into health-focused and environmentally

sustainable products (Bernaerts et al., 2018). Their multifunctional nature ensures their relevance across therapeutic, functional, and clean-label food markets, offering promising avenues for future development.

2.3. Vitamins

Microalgae represent a potent source of essential vitamins, offering significant nutritional and therapeutic benefits that position them as natural biofortifiers in food systems. Species such as *Chlorella vulgaris* and *Nannochloropsis gaditana* are particularly rich in B vitamins, including B2, B3, and the rare B12, which supports energy metabolism and neurological health. *Chlorella vulgaris* provides B12 concentrations ranging from 0.3 to 3.2 mg/kg, addressing a critical dietary gap in plant-based diets (Ljubic et al., 2020; Mehariya et al., 2021).

In another study shows that *S. maxima*, a species of algae widely cultivated for human consumption, contains up to 71% crude protein with high levels of vitamin B1, vitamin B2, and adequate concentrations of all essential amino acids except those containing β -carotene and sulfur (Clément et al., 1967). Since protein is thought to be the most expensive nutrient in animal feed, developing natural alternatives to soybean meal may be cost competitive (Lum et al., 2013).

In addition to water-soluble vitamins, microalgae such as *Dunaliella bardawil* serve as excellent sources of pro-vitamin A and vitamin E, promoting immune function, skin health, and antioxidant defense (Pan-utai et al., 2021). Furthermore, *Tetraselmis chuii* and *Euglena gracilis* produce abundant vitamin C, enhancing their appeal as natural fortification agents. Notably, *Arthrospira maxima* and *Tetraselmis suecica* also contain significant amounts of vitamin D, critical for bone health and immune regulation, with concentrations reaching up to 14 mg/g (Ljubic et al., 2020).

The ability of microalgae to produce a wide range of bioavailable vitamins, including antioxidants like vitamins C and E, aligns with consumer demand for natural, health-promoting food ingredients (Torres-Tiji et al., 2020). This exceptional nutrient density makes microalgae an attractive alternative to synthetic vitamin fortification, offering sustainable solutions to combat dietary deficiencies while supporting the clean-label trend.

2.4. Peptides

Peptides derived from microalgae have emerged as valuable bioactive components with multifunctional health benefits. Species such as *Spirulina* and *Chlorella vulgaris* are particularly rich in protein, with up to 70% of biomass composed of peptides known for their antioxidant, antimicrobial, and antihypertensive properties (Ambati et al., 2014; Bernaerts et al., 2018). These bioactive peptides contribute to food preservation and human health by reducing

oxidative stress, inhibiting microbial growth, and promoting cardiovascular health.

For instance, hydrolyzed peptides from *Chlorella vulgaris* exhibit potent free radical-scavenging activity, neutralizing harmful hydroxyl and superoxide radicals (Mtaki et al., 2020). Similarly, enzymatic hydrolysates from *Navicula incerta* demonstrate significant antioxidant effects, offering potential therapeutic applications in managing oxidative stress and metabolic disorders (Heo et al., 2005). These peptides also enhance food functionality and texture, aligning with the growing demand for natural and multifunctional food additives.

Advanced enzymatic hydrolysis techniques have further optimized the extraction of bioactive peptides, enhancing their therapeutic efficacy and commercial viability. As natural alternatives to synthetic additives, microalgal peptides hold significant potential for innovation in both functional food and nutraceutical markets.

3. High-Value Microalgae Secondary Metabolites

3.1. Phytosterols

Phytosterols extracted from microalgae species like *Nannochloropsis* and *Chlorella* have shown significant cholesterol-lowering properties. Structurally similar to cholesterol, these compounds compete with dietary cholesterol for intestinal absorption, reducing LDL cholesterol levels and lowering the risk of cardiovascular disease (Nollet & Ahamad, 2024). This mechanism provides a sustainable alternative to pharmacological lipid-lowering agents, particularly for individuals with hypercholesterolemia (Moghadasian & Frohlich, 1999).

The integration of microalgal phytosterols into functional foods addresses consumer demand for heart-healthy, natural ingredients. Their dual role as therapeutic agents and sustainable alternatives to synthetic cholesterol-lowering compounds underscores their transformative potential in the nutraceutical and functional food industries.

3.2. Mycosporine-Like Amino Acids (MAAs)

Mycosporine-like amino acids (MAAs) are unique compounds synthesized by certain microalgae, notably red algae such as *Porphyridium*. These bioactive molecules serve as natural photoprotective agents, absorbing ultraviolet (UV) radiation and mitigating oxidative damage to cellular components such as DNA and proteins (Garcia-Pichel & Castenholz, 1993). This functionality renders MAAs particularly valuable in applications related to skincare and sun protection.

Beyond their role in UV defense, MAAs exhibit potent antioxidant properties that delay oxidative spoilage in food products, thereby extending shelf life while simultaneously

delivering health benefits (Ambati et al., 2014). Their multifunctionality (including UV absorption, antioxidant activity, and photoprotection) makes them appealing for incorporation into anti-aging and photoprotective formulations in the cosmetic and food industries (Pan-utai et al., 2021). By offering natural, sustainable solutions to combat oxidative stress and radiation damage, MAAs align with increasing consumer preferences for eco-friendly, health-enhancing products.

3.3. Pigments

3.3.1. Phenolic compounds

Phenolic compounds produced by microalgae, including flavonoids and phenolic acids, are renowned for their antioxidant, anti-inflammatory, and anticancer properties. Species such as *Phaeodactylum tricornutum*, *Chlorella vulgaris*, and *Haematococcus pluvialis* produce bioactive phenolics, including apigenin, genistein, and p-coumaric acid, which exhibit strong therapeutic potential (Goiris et al., 2012). For example, apigenin promotes autophagy in leukemia cells, while ferulic acid and p-coumaric acid demonstrate robust free radical scavenging activities, reducing oxidative stress and enhancing cellular health (Heo et al., 2005).

Beyond health benefits, phenolic compounds act as natural preservatives, delaying lipid peroxidation and enhancing food stability. This dual functionality underscores their importance in developing functional foods and nutraceuticals that prioritize both sustainability and health outcomes (Goiris et al., 2012).

3.3.2. Chlorophyll

Although food processing effects are well established, a more complete understanding of chlorophyll derivatization by digestion, the extent to which chlorophyll derivatives are absorbable, and the absorption and formation of any specific chlorophyll metabolites is absolutely necessary to better understand the role these pigments may play in the prevention of chronic diseases (Ferruzzi & Blakeslee, 2007).

Chlorophyll, abundantly found in *Chlorella* and *Spirulina*, serves as a natural green colorant and detoxifying agent. Its health benefits, including support for liver function and improved digestion, enhance its appeal in health-oriented and detox products (Ambati et al., 2014; Caporgno & Mathys, 2018).

The growing interest in the potential chemopreventive effects of chlorophyll stems from its role as a class of plant pigments associated with cancer prevention, particularly in diets rich in phytochemicals. Chlorophyll derivatives, traditionally used in medicine, are notable for their low toxicity, making them promising candidates as anti-cancer and therapeutic agents. The following sections explore studies that detail the in vitro and in vivo bioactivity of chlorophyll, along

with the potential mechanisms underlying its anti-cancer actions (Harrison et al., 1954; Kephart, 1955).

In another study, consuming chlorophyll at each meal led to an overall 55% reduction in mean urine levels of the aflatoxin biomarker compared to those taking a placebo. Therefore, prophylactic interventions or supplementing the diet with chlorophyll-rich foods may be a practical way to prevent the development of hepatocellular carcinoma or other cancers of environmental origin (Egner et al., 2001).

3.3.3. Phycobiliproteins

Phycobiliproteins, such as phycocyanin and allophycocyanin, are vibrant protein-based pigments synthesized by microalgae, including *Spirulina platensis*. These pigments serve dual roles as natural colorants and bioactive compounds, exhibiting antioxidant, anti-inflammatory, and hepatoprotective properties (Citi et al., 2024). Phycocyanin, for example, has demonstrated potential in managing oxidative stress, inflammatory diseases, and liver conditions, making it suitable for functional foods and nutraceuticals (Eriksen, 2016).

Moreover, allophycocyanin offers immunomodulatory and anti-inflammatory benefits, further enhancing its value in addressing chronic health conditions. These pigments' ability to combine aesthetic appeal with therapeutic functionality positions them as innovative alternatives to synthetic dyes, catering to health-conscious and sustainability-focused markets (Lucas et al., 2018).

3.3.4. Carotenoids

Carotenoids, including astaxanthin, lutein, β -carotene, and fucoxanthin, are among the most valuable microalgal metabolites due to their potent antioxidant properties and diverse health benefits. Astaxanthin, derived primarily from *Haematococcus pluvialis*, is particularly notable for its superior antioxidant capacity, neuroprotective effects, and applications in cardiovascular health and skincare (Ambati et al., 2014; Jannel et al., 2020; Shah, et al., 2016).

Astaxanthin has demonstrated significant anti-inflammatory properties in an in vitro study using LPS-stimulated RAW264.7 mouse macrophage cells. It was shown to inhibit the synthesis of proinflammatory mediators, including nitric oxide (NO) and prostaglandin E2 (PGE2), which are produced by inducible nitric oxide synthase (iNOS) and cyclooxygenase-2 (COX-2), respectively. Additionally, astaxanthin suppressed the production of key cytokines such as tumor necrosis factor-alpha (TNF- α) and interleukin-1 beta (IL-1 β). A notable mechanism underlying these effects is its ability to inhibit the activation of nuclear factor kappa B (NF- κ B), a transcription factor that regulates the expression of proinflammatory genes, including iNOS, COX-2, TNF- α , IL-1 β , and interleukin-6 (IL-6). Astaxanthin also reduced iNOS

promoter activity and directly inhibited intracellular reactive oxygen species (ROS) accumulation, as well as hydrogen peroxide (H₂O₂)-induced NF- κ B activation and the subsequent expression of iNOS and COX-2. Furthermore, it blocked nuclear translocation of the NF- κ B p65 subunit and prevented the degradation of I κ B- α by inhibiting I κ B kinase (IKK) activity. These findings collectively indicate that astaxanthin suppresses inflammatory mediator production through a multifaceted mechanism involving the inhibition of NF- κ B activation, IKK activity, and I κ B- α degradation (Lee et al., 2003).

Lutein, abundant in *Chlorella* and *Dunaliella salina*, supports eye health by mitigating risks of macular degeneration and cataracts (Nwachukwu et al., 2016). Meanwhile, β -carotene serves as both a natural food colorant and a precursor to vitamin A, with immune-boosting and skin-protecting properties that cater to clean-label preferences (Bernaerts et al., 2018). Fucoxanthin, found in *Chaetoceros sp.*, exhibits anti-obesity, anti-diabetic, and anticancer properties, making it a promising candidate for metabolic health interventions (Fernandes & Mamatha, 2023).

Although production costs remain high for certain carotenoids like astaxanthin, advancements in photobioreactor genetic engineering and technologies continue to enhance yield and cost-efficiency, solidifying their role in sustainable food systems (Pan-utai et al., 2021).

4. Conclusion

Investigating bioactive compounds derived from microalgae highlights their significant potential as sustainable and multifunctional food additives. Microalgae provide a variety of compounds, including polyunsaturated fatty acids (PUFAs), vitamins, peptides, and secondary metabolites like carotenoids, chlorophyll, and phytosterols, meeting contemporary consumer preferences for natural, health-enhancing, and eco-friendly ingredients (Ambati et al., 2014; Caporgno & Mathys, 2018; Pan-utai et al., 2021). Positioning microalgae as a key contributor to functional food innovation, these compounds offer health benefits ranging from antioxidant and anti-inflammatory effects to cardiovascular and vision support (Cioanca et al., 2024)

Moreover, the ecological benefits of microalgae cultivation—including reduced water and land use and compatibility with controlled growth systems—highlight their suitability as a sustainable food source. Microalgae such as *Schizochytrium* and *Nannochloropsis* exemplify the ability to produce eco-friendly omega-3 fatty acids, addressing the growing demand for plant-based alternatives while alleviating pressure on marine ecosystems (Pan-utai et al., 2021).

Despite these advantages, challenges such as high production costs, complex extraction processes, and regulatory

hurdles must be addressed to enable widespread commercialization. Innovations in cultivation methods, including photobioreactors and genetic engineering, show promise in reducing costs and enhancing yields, but further research and policy support are essential (Bernaerts et al., 2018; Pan-utai et al., 2021).

In summary, microalgae offer a compelling solution to the dual imperatives of health promotion and environmental sustainability in food systems. As advancements in technology and regulation progress, microalgal bioactives hold the potential to revolutionize global food markets, paving the way for a more sustainable and health-focused future (Ambati et al., 2014; Caporgno & Mathys, 2018).

Conflict of Interest

The authors declare no conflict of interest.

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