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The Impact of Marine Algae on Health and Physical Performance: A Literature Review

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Abstract

Introduction: Marine algae are rich in bioactive compounds with diverse health-promoting effects. Their ability to thrive in extreme marine environments results in the synthesis of unique metabolites.

Methodology: A review was conducted using PubMed, Google Scholar, and ResearchGate. Search terms included: algae, Spirulina, Chlorella, supplement, health, sport, toxicity. Studies published between 2011 and 2024 were reviewed.

Results: Algae contain compounds that exhibit antioxidant, anti-inflammatory, anticancer, neuroprotective, antimicrobial, and metabolic regulatory properties. They have demonstrated potential in improving outcomes in conditions such as diabetes, cardiovascular disorders, neurodegenerative diseases, and cancer. Additionally, Spirulina has been shown to enhance physical performance and support recovery in athletes. However, concerns regarding heavy metal accumulation and lack of product standardization have also been noted.

Conclusions: Algae offer broad therapeutic potential in nutrition and both preventive and curative medicine. Nevertheless, further human studies and the development of regulatory standards are necessary to guarantee the safety and efficacy.

Keywords: algae, Spirulina, Chlorella, supplement, health, sport, toxicity

1. Introduction

Marine algae, including macroalgae (seaweeds) and microalgae, are aquatic photosynthetic organisms recognized for their nutritional richness in bioactive compounds. They are classified into green (Chlorophyta), red (Rhodophyta), and brown (Phaeophyceae) algae, each with unique pigments and properties. As a result of their adaptation to harsh environments, algae synthesize a broad array of biologically active substances—such as fucoidan, laminarin, astaxanthin, phycocyanin, stigmasterol, polyunsaturated fatty acids, and essential micronutrients. These substances exhibit antioxidant, anti-inflammatory, antimicrobial, neuroprotective, and metabolic benefits [1,2,3]. Recently, marine algae have attracted attention in sports nutrition, where their benefits for recovery and endurance are being actively explored [4]. Spirulina (*Arthrospira platensis*) and Chlorella (*Chlorella vulgaris*) are the most popular algae supplements due to their wide availability and well-documented health- promoting properties [5,6].

This review synthesizes current evidence on the health benefits of marine algae, with particular emphasis on their functional components, mechanisms of action and potential applications in medicine and nutrition.

2. Methodology

To conduct a comprehensive review of the health-promoting properties of marine algae, articles available in PubMed, Google Scholar and ResearchGate databases were analyzed. The following keywords were used in the search: algae, Spirulina, Chlorella, supplement, health, sport, toxicity. The search included studies published between 2011 and 2024. Reference lists of selected studies were also screened to identify additional relevant sources.

3. Nutritional Compounds

Marine algae are recognized as a rich source of essential macronutrients, including proteins, carbohydrates, and lipids. Microalgae such as Spirulina and Chlorella contain high amounts of protein, ranging from 51% to 70% of their dry weight, and provide all essential amino acids that mammals are unable to synthesize [5,6,7]. In comparison to terrestrial sources such as meat or legumes, algal proteins are highly digestible and bioavailable, making them suitable for individuals with digestive disorders or increased nutritional demands [8]. Although the protein efficiency ratio (PER) of blue-green algae is lower than that of animal protein, it is still higher than in most plant-based proteins [6]. This makes algae particularly valuable in protein-deficient diets, especially in developing countries where undernutrition is a public health challenge [6,9]. Moreover, algal lipids contain polyunsaturated fatty acids, particularly omega-3 and omega-6, which are essential for the proper functioning of the cardiovascular and immune systems due to their role in the synthesis of prostaglandins and leukotrienes. Their beneficial effects on diseases such as cancer, diabetes, cardiovascular disorders, arthritis, and Alzheimer's disease further underscore their nutritional significance [9]. Algal fatty acids have gained attention as a safer alternative to fish-derived oils, as they contain lower levels of environmental contaminants, such as mercury and dioxins [5]. Algae also synthesize considerable amounts of carbohydrates, including polysaccharides such as laminarin and fucoidan, which will be discussed in greater detail in the following sections of this review [10].

In addition to macronutrients, marine algae provide a diverse range of micronutrients vital for human health. They are rich in vitamins such as A, D, E, K, C, and B-complex, especially vitamin B12 (cobalamin), which is notably scarce in plant-based foods [6,9]. This makes algae particularly valuable in vegetarian and vegan nutrition [3]. However, the bioavailability of algal-derived B12 remains controversial. While some studies have reported increased B12 levels after algal supplementation, others argue that the analogues of cobalamin present in Spirulina may not be biologically active. Nonetheless, certain species, such as Chlorella and nori, have shown potential in preventing B12 deficiency among vegans [3]. Moreover, algae are an important source of trace elements such as iron and iodine. Spirulina, in particular, provides highly bioavailable iron in concentrations significantly higher than those found in many plant-based foods and even some animal products, without causing gastrointestinal side effects such as diarrhoea. This makes it especially beneficial in combating iron-deficiency anemia, particularly among vulnerable populations such as pregnant women and children [9]. Iodine is another essential micronutrient that is abundant in marine algae, particularly in brown seaweeds like *Laminaria* and *Saccharina*.

Its concentration varies widely among species and can be significantly affected by processing and preparation methods. For example, boiling can reduce iodine content by up to 75%. Although moderate consumption of iodine-rich algae supports proper thyroid function, excessive intake may increase the risk of thyroid dysfunction including both hyperthyroidism and hypothyroidism [3].

4. Antioxidant Effects

Reactive oxygen species (ROS) are naturally produced during cellular metabolism and immune responses, but their levels can also rise due to external factors such as environmental pollution, unhealthy diet, smoking, sleep deprivation, and exposure to ultraviolet or ionizing radiation. If not adequately neutralized, ROS contribute to oxidative stress, cellular dysfunction, and damage to lipids, proteins, and DNA [5]. Algae are increasingly recognized as rich sources of natural antioxidants, due to their content of carotenoids, phenolic compounds, and vitamins. These bioactive molecules play a crucial role in protecting cells from oxidative stress, which contributes to the development of numerous diseases, including Alzheimer's disease, Parkinson's disease, atherosclerosis, rheumatoid arthritis, cancer, and diabetes, as well as premature aging [1,5,11,12].

Blue-green algae (BGA) have demonstrated antioxidant effects in human clinical studies.

In diabetic patients, supplementation with 8 g/day of Spirulina for 12 weeks led to a significant reduction in malondialdehyde (MDA) levels - a biomarker of lipid peroxidation and oxidative stress. The antioxidant properties of algae are further enhanced by their content of essential micronutrients, including vitamins C, E, and B12, as well as phycocyanin (PC), which has been identified as a key antioxidant component in blue-green algae [11].

Moreover, natural antioxidants produced by algae, including tocopherols, flavonoids, phlorotannins, and alkaloids, are considered effective in reducing the risk of cardiovascular diseases, certain cancers, and other chronic conditions. They also show promise as safe and cost-effective adjuncts in the management of diabetes and protecting organs from oxidative damage [12].

Finally, these findings underscore the therapeutic potential of algae-derived antioxidants in enhancing cellular defense mechanisms and preventing numerous chronic diseases.

5. Anti-Inflammatory and Immunomodulatory Properties

Marine algae possess potent anti-inflammatory and immunomodulatory properties, largely due to phytosterols such as stigmasterol, sulfated polysaccharides like laminarin, and polyunsaturated fatty acids.

Stigmasterol, a bioactive sterol, has demonstrated effective anti-inflammatory and analgesic activity. It has been shown to alleviate cartilage degradation in rodent models of osteoarthritis and, when combined with mesenchymal stem cell secretome, reduce inflammation and promote cartilage regeneration. Furthermore, stigmasterol decreases the release of pro-inflammatory mediators such as tumor necrosis factor-α (TNF-α), nitric oxide (NO), interleukins IL-1β and IL-6, and inhibits cyclooxygenase-2 (COX-2) activity. It also enhances the mucosal immune response in inflammatory bowel disease (IBD) by activating the butyrate-PPARγ axis and stimulating both specific and non-specific immune responses [13].

Additionally, algal extracts exert their anti-inflammatory effects through several molecular mechanisms. These include the inhibition of pro-inflammatory cytokine and eicosanoid production, downregulation of genes encoding pro-inflammatory enzymes, and interference with key signaling pathways [5].

Laminarin, a sulfated polysaccharide from brown algae, is another compound with notable immunomodulatory and anti-inflammatory potential. Recognized as a dietary fiber, it enhances immune activity by stimulating the accumulation of B cells and helper T cells. Laminarin promotes wound healing by supporting fibroblast adhesion and facilitates bone regeneration via osteoblast stimulation. Studies in animal models have demonstrated laminarin's ability to modulate gut immune responses and improve intestinal health. These effects are likely mediated through changes in the expression of pro- and anti-inflammatory genes, and reduced secretion of inflammatory cells in liver, positioning laminarin as a promising agent for managing inflammatory conditions such as ulcerative colitis and Crohn's disease [14].

Collectively, these findings highlight the multifaceted anti-inflammatory effects of algae-derived compounds and their potential as natural therapeutic agents in inflammatory and immune-mediated diseases.

6. Anticancer Properties

Marine algae are increasingly valued for their anticancer potential, mainly through regulating apoptosis, proliferation, migration, and angiogenesis. Apoptosis, programmed cell death, is crucial for maintaining cellular homeostasis and preventing uncontrolled cell growth and is a major target in cancer therapy. Numerous studies have shown that specific algal extracts can induce apoptosis in various cancer cell lines through mechanisms involving oxidative stress and modulation of proteins [2,10].

For instance, fucoidan, a sulfated polysaccharide derived from brown algae, has been revealed to induce apoptosis in human colon cancer cells. Similarly, marine algae such as *Colpomenia sinuosa, Halimeda discoidea*, and *Galaxaura oblongata* have demonstrated antitumor activity in hepatoma and leukemia cell lines, primarily by promoting the generation of ROS, which act as mediators of the apoptotic signaling pathway [1].

Further insight comes from research on *Colpomenia sinuosa*, whose extract significantly inhibited the proliferation and migration of colon cancer cells. These effects were associated with increased ROS levels, upregulation of the pro-apoptotic protein p21, and downregulation of the anti-apoptotic protein Bcl-2, while exhibiting minimal cytotoxicity toward healthy cells [2].

Among algae-derived compounds, stigmasterol, found in the microalga *Navicula incerta*, has demonstrated anticancer properties across various tumor types, including skin, breast, lung, gastric, cervical, and ovarian cancers. These effects occur through the activation of pro-apoptotic proteins, regulation of multiple signaling pathways, suppression of chemoresistance, and enhancement of the activity of certain antiproliferative drugs. In breast cancer cell lines, stigmasterol boosted the antitumor activity of sorafenib, suppressed angiogenic mediators, downregulated the proliferative marker Ki-67, and increased caspase-3 activity while reducing levels of the anti-apoptotic protein Bcl-2 [13].

S-laminaran has also been shown to reduce metastasis *in vivo* by inhibiting heparanase, an enzyme involved in the degradation of components of the basement membrane and extracellular matrix, whose expression is strongly associated with tumor progression [10]. Altogether, these findings underscore the therapeutic potential of marine algae and their bioactive metabolites as natural sources of anticancer agents.

7. **Neuroprotective Effects**

Neurodegenerative diseases such as Alzheimer’s, Parkinson’s, and multiple sclerosis are characterized by progressive neuronal damage, oxidative stress, and chronic inflammation.

In the context of Alzheimer’s disease (AD), several microalgal species, such as *Chlorella vulgaris*, *Haematococcus pluvialis, Nannochloropsis oculata, Neochloris oleoabundans*, and *Chaetoceros calcitrans*, have demonstrated protective effects against β-amyloid-induced neurotoxicity and oxidative stress in neuronal cells. These properties are primarily attributed to their high carotenoid content, including astaxanthin and β-carotene [1]. Additionally, stigmasterol has shown promise in managing neurodegenerative diseases through its inhibition of acetylcholinesterase and ability to modulate the GABAergic system. It also reduces oxidative stress, DNA damage, and excitotoxicity, while enhancing antioxidant defenses and nitric oxide synthase expression [13]. Moreover, studies have revealed that Spirulina extract can inhibit lipopolysaccharide-induced microglial activation and mitigate neuroinflammation, a key factor in diseases such as Parkinson’s, multiple sclerosis, and AD. This neuroprotection has also been observed in animal models of spinal cord injury, where Spirulina promoted neural tissue recovery [9].

Beyond neurodegeneration, algae-derived compounds have also shown therapeutic potential in affective disorders. A randomized clinical trial involving 92 patients with major depression demonstrated that supplementation with an antioxidant-rich extract from *Chlorella vulgaris* (Algomed®) improved somatic and cognitive symptoms of depression and anxiety after six weeks, when used as an adjunct to standard antidepressant therapy. Similarly, astaxanthin from *Haematococcus pluvialis* was found to significantly reduce depression and fatigue scores in adults, supporting its role in mood regulation [15].

To sum up, these findings suggest that algae may offer a promising, multi-targeted nutritional approach for supporting neurological health and mood stability. Nevertheless, further randomized controlled trials are warranted to confirm these effects [15].

8. Antimicrobial Effects

The growing problem of antibiotic resistance among clinical pathogens highlights the relevance of algal metabolites as alternative antimicrobials. Marine algae produce a broad spectrum of bioactive substances with potent antibacterial effects, including phlorotannins, fatty acids, terpenoids, polysaccharides, alkaloids, and halogenated furanones. Early studies revealed that extracts from *Chlorella vulgaris* inhibited the growth of *Pseudomonas aeruginosa*, *Staphylococcus aureus*, *Streptococcus pyogenes*, and *Bacillus subtilis*. Additionally, fatty acids isolated from brown algae such as *Sargassum vulgare* and *Sargassum fusiforme* induced morphological disruption of bacterial cells, including perforation of the cell wall, cytoplasmic leakage, and shrinkage of cellular structures in *Staphylococcus aureus* and *Klebsiella pneumoniae*. Polysaccharides such as fucoidan and laminarin have also been reported to exert antibacterial effects by interfering with bacterial DNA function. These compounds have demonstrated effectiveness against *Staphylococcus aureus* and *Escherichia coli*, as well as in preventing the adhesion of *Helicobacter pylori* to the gastric mucosa [16]. Moreover, stigmasterol has shown both bacteriostatic and bactericidal activity against a broad spectrum of Gram-positive and Gram-negative bacteria, primarily by blocking translation processes [13].
Beyond antibacterial potential, marine algae have also emerged as promising antiviral agents. Red and brown seaweeds are rich sources of sulphated polysaccharides such as carrageenan’s, fucoidans, and ulvans. By acting at various stages of the viral life cycle - including attachment, penetration, internalization, uncoating, and replication - these compounds inhibit a wide range of pathogens, such as human immunodeficiency virus (HIV), hepatitis C virus (HCV), dengue virus (DENV), herpes simplex viruses (HSV-1 and HSV-2), human papillomavirus (HPV), and numerous respiratory tract viruses. Carrageenans were found to be potent inhibitors of infection by specific sexually transmitted types of HPV. Contraceptives lubricated with carrageenans can effectively block HPV transmission during sexual contact without causing anticoagulant effects or cytotoxicity. Moreover, carrageenan isolated from *Gigartina skottsbergii* has been shown to inhibit the activity of HSV-1 and HSV-2. It interferes with the interaction between cell surface heparan sulfate and HSV glycoproteins at an early stage of infection, leading to the denaturation and inactivation of the viral glycoproteins. Additionally, fucoidan extracted from the brown macroalga *Sargassum swartzii* revealed inhibitory effects on HIV-1 by suppressing the expression of the HIV-1 p24 antigen and the activity of reverse transcriptase [10,17]. Similarly, another study demonstrated that the antiretroviral activity of *Dictyota menstrualis* was attributed to two diterpene compounds that interfered with an early stage of the HIV-1 replication cycle [18]. Furthermore, polysaccharides from marine algae have been explored in the formulation of nasal sprays and coatings for personal protective equipment to prevent viral transmission during the COVID-19 pandemic [17]. These findings support the therapeutic potential of algae-derived compounds in the development of novel antimicrobial agents.

9. Support in Metabolic Disorders

Metabolic disorders are a broad group of conditions resulting from disturbances in the metabolic pathways, including non-alcoholic fatty liver disease (NAFLD), hyperlipidemia, diabetes, and hypertension.

Clinical and preclinical studies suggest that supplementation with BGA may exert hepatoprotective effects and improve lipid profiles. One study reported that daily intake of 4.5 g of BGA for three months reversed liver damage and significantly reduced total cholesterol and triglyceride levels in patients with NAFLD. These benefits may be attributed to lowered hepatic lipid accumulation and inhibition of intestinal cholesterol absorption, although larger randomized trials are needed to confirm these outcomes in humans [11].

Spirulina has shown particular promise in supporting cardiovascular and metabolic health. A 2015 review and a 2018 meta-analysis revealed that *A. platensis* supplementation significantly reduced levels of total cholesterol, low-density lipoprotein (LDL), very low-density lipoprotein (VLDL), triglycerides, fasting blood glucose, and diastolic blood pressure [19].

Algal extracts also exhibit potent antidiabetic properties. In diabetic rats, administration of *A. platensis* extract improved glucose levels, liver and kidney function markers, protein profiles, and body weight. Additionally, *Ulva lactuca* was found to alleviate insulin resistance and support regeneration of pancreatic β-cells, while also promoting reverse cholesterol transport. The nephroprotective properties of Spirulina have also been documented. In diabetic-induced rats, supplementation reduced urea and creatinine levels - key markers of renal dysfunction - likely through antioxidant activity and improved glomerular filtration [12].

Spirulina supplementation has been associated with beneficial effects on blood pressure regulation. While some studies observed a decrease in diastolic blood pressure alongside a slight increase in systolic blood pressure, others reported a reduction in both, following a daily intake of 4.5 g for six weeks. The antihypertensive effects of *A. platensis* are believed to result from vasodilatory mechanisms, as demonstrated in animal models. Additionally, its favorable mineral profile - characterized by high potassium and low sodium content - contributes to its blood pressure-lowering properties [9].

Taken together, these findings highlight the multifaceted role of algae in the management of metabolic disorders. Through lipid regulation, glycemic control, organ protection, and vasodilation, algae-derived supplements represent a promising adjunct strategy in the prevention and treatment of chronic metabolic diseases.

10. Marine Algae in Sports

Arthrospira platensis has gained popularity as a nutraceutical supplement among physically active individuals due to its high-quality protein content and bioactive phytonutrients, which exhibit potent antioxidant activity. Regular physical activity, especially at high intensities, increases the production of ROS, which may cause oxidative damage, fatigue, and impair immune function. Spirulina supplementation has been shown to help mitigate these effects by improving redox balance, enhancing hemoglobin levels, and potentially reducing inflammation and muscle damage [4].

For instance, studies conducted on elite rugby players demonstrated that daily intake of 5,7 g of *A. platensis* may prevent exercise-induced inflammation and accelerate recovery within 24 hours post-exercise. This protective effect is thought to result from Spirulina's antioxidant properties and high iron content, which support hemoglobin synthesis and enhance oxygen delivery to muscles. In endurance athletes, such as cyclists or runners, Spirulina supplementation at doses of 6–7.5 g/day may improve fatigue tolerance and redox balance. However, its ergogenic benefits seem limited in power athletes, as most studies report no significant impact on performance parameters such as strength or speed [4].

Beyond performance, *A. platensis* may also play a role in supporting satiety and body composition. In one study involving obese individuals, Spirulina supplementation combined with a calorie-restricted diet significantly reduced body weight, BMI, waist circumference, and body fat [19]. Altogether, current evidences suggest that Spirulina may serve as a valuable adjunct in the nutrition strategies of endurance athletes, with possible benefits in redox regulation, recovery, and body composition.

11. Gut Microbiota and Prebiotic Potential

Marine algae, particularly red seaweeds and cyanobacteria, exhibit notable prebiotic properties, largely due to their high carbohydrate content, which acts as biostimulants for beneficial intestinal bacteria [9]. In one study, supplementation with the red macroalga *Chondrus crispus* led to significant improvements in the gut microbiota of rats, including an increased abundance of beneficial bacterial strains, enhanced colonic histomorphology, and immune function, as evidenced by elevated levels of immunoglobulins A and G [20].

Similarly, the extract of Spirulina has been identified as a rich source of key biostimulatory compounds such as xylose, galactose, and resistant starch [9]. Biomass from *A. platensis* has also been shown to selectively promote the proliferation of probiotic strains, including *Lactobacillus casei, L. acidophilus, Streptococcus thermophilus*, and *Bifidobacterium spp.*, while simultaneously inhibiting the growth of harmful pathogens such as *Proteus vulgaris, Bacillus subtilis, Enterobacter spp.*, and *Clostridium spp.* [9,20]. This modulation of gut flora by algae has been associated with broader health benefits, including enhanced immunity and improved metabolic function, and may contribute to the prevention of disorders such as inflammatory bowel disease (IBD), which positions them as promising functional foods [9].

12. Safety and Toxicological Considerations

Despite numerous health benefits, algae consumption may pose toxicological risks due to possible contamination with heavy metals, pathogenic microorganisms, and the presence of natural toxins or allergenic compounds.

Toxicological studies on Spirulina indicate a high safety margin. Oral administration of up to 800 mg/kg in rats produced no mortality or adverse effects on organ function or histopathology. Even at high dietary levels (up to 48% over 86 weeks), Spirulina showed no signs of toxicity in rodents. Only one study, in which mice received a diet containing 60% algae, reported increased organ weights and the occurrence of nephrocalcinosis. Nonetheless, fertility and reproduction studies showed no adverse outcomes following Spirulina treatment at dietary levels of up to 30%, suggesting that Spirulina is non-toxic at levels far exceeding typical human consumption [6].

However, the safety of marine algae depends on several factors. Seaweeds can bioaccumulate heavy metals such as arsenic, cadmium, lead, and mercury, due to their affinity for chemical groups. The degree of accumulation varies with algal species, environmental conditions, and anthropogenic contamination. One study assessed health risks using bioaccumulation factors (BAF) and calculated the Hazard Index (HI) for both children and adults. While the overall HI for adults remained below the safety threshold (<1), four seaweed species showed an HI greater than 1 for children, indicating a potential toxicological risk and the need to control consumption in this population group [21]. Additionally, concerns exist regarding allergenicity and contamination. Cases of human poisoning have been associated with wild-harvested Spirulina contaminated with toxin-producing cyanobacteria such as *Microcystis*. This highlights the need for controlled cultivation and regular testing [3].

Moreover, the lack of regulation for algae-based dietary supplements raises additional problems, as it can result in significant variability between batches produced by the same manufacturer [7]. To ensure consumer safety, seaweed processing methods such as washing or boiling are recommended to reduce both heavy metal content and microbial contamination. Furthermore, quality control during harvest and storage is essential to preserve nutritional value while minimizing toxicological risks [21].

13. Conclusions

Marine algae represent a valuable and underutilized resource in human health and nutrition.

The wide spectrum of bioactive compounds found in these organisms—ranging from polysaccharides and sterols to pigments and polyphenols—contributes to their diverse biological effects, including antioxidant, anti-inflammatory, anticancer, neuroprotective, antimicrobial, and metabolic activities. Evidence from *in vitro, in vivo*, and clinical studies demonstrates that algae-derived supplements may serve as effective adjuncts in the management of chronic diseases, including diabetes, cardiovascular disorders, neurodegenerative conditions, and cancer. Moreover, their potential to enhance physical performance, support recovery, and modulate the gut microbiota positions algae as promising functional ingredients.

Despite encouraging findings, challenges remain regarding the standardization, bioavailability, and safety of algal products. The lack of consistent regulation and the possibility of contamination necessitate strict quality control and further clinical validation. Nevertheless, marine algae offer a sustainable, natural, and multifunctional approach to health promotion and disease prevention. With ongoing research and technological advancements, their integration into evidence-based dietary and therapeutic strategies is likely to expand in the coming years.

Disclosure:

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