



Review

Exploring the Health Benefits of Nutraceuticals Derived from Marine Sources—A Review

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Abstract: With increasing research underscoring the link between good health and food biochemistry, there is a pressing need to utilize sustainable food sources that offer health advantages beyond nourishment. This review explores the emerging field of functional ingredients and their application as nutraceuticals to promote human health. Functional ingredients derived from natural sources, such as marine organisms, possess bioactive properties that provide health benefits beyond basic nutrition. This review focuses on key categories of marine-derived compounds, examining their mechanisms of action and therapeutic potential. Emphasis is placed on recent scientific findings, clinical trials, and the growing demand for nutraceuticals as preventive and therapeutic agents. In conclusion, the incorporation of cutting-edge functional components into nutraceuticals represents a significant advancement in promoting health and well-being. These components possess bioactive properties that could be beneficial in managing and preventing chronic diseases while providing additional nutritional value. However, to fully harness the potential of these innovative functional components as nutraceuticals, further research, comprehensive safety assessments, and robust regulatory measures are necessary.

Keywords: nutraceuticals; health benefits; plant; marine; microbes

1. Introduction

The domain of nutraceuticals has undergone considerable expansion in recent decades, propelled by an increasing consumer demand for health-enhancing foods and a more profound comprehension of the interplay between dietary practices and the prevention of chronic illnesses [1]. Nutraceuticals, defined as bioactive substances that confer therapeutic or health advantages extending beyond rudimentary nutrition, have emerged as a central focus within both academic research and industrial applications [2]. This growing interest epitomizes a worldwide movement towards preventive healthcare and accentuates the significance of dietary choices in the management and alleviation of health-related conditions [3]. Concurrently, the global nutraceutical industry has experienced rapid growth, with a recent report projecting that the US market will attain 578.23 million USD by 2050, positioning it as a leader in the sector [4]. Central to this paradigm shift are groundbreaking functional ingredients, which are naturally occurring compounds endowed with specific physiological advantages [5]. These ingredients, extracted from botanical sources, marine life, and microorganisms, exhibit distinctive biochemical characteristics that can modulate various metabolic processes and promote overall well-being (Figure 1). The diversity of functional ingredients is extensive, including polyphenols, flavonoids, carotenoids, probiotics, prebiotics, peptides, and bioactive lipids, each playing a pivotal role in the advancement of sophisticated nutraceutical formulations [6,7].

In numerous nations, initiatives aimed at regulating functional foods, dietary supplements, and nutraceuticals are underway; however, these products have yet to attain formal legal recognition, and a scientific consensus on the delineation of these categories remains elusive. Innovative functional ingredients are at the vanguard of the nutraceutical evolution. Derived from marine sources, these ingredients are characterized by unique biochemical



properties and specific physiological impacts (Figure 2). Their capacity to modulate metabolic pathways, bolster immune responses, and mitigate oxidative stress and inflammation positions them as promising candidates for addressing widespread health challenges, including diabetes, cardiovascular diseases, obesity, and neurodegenerative conditions [8]. Nevertheless, experts commonly concur that foods exhibiting physiological advantages that extend beyond basic nutrition and that diminish the risk of chronic diseases or their manifestations are classified as functional foods [9]. Despite this comprehensive and coherent definition, scholars misunderstand the terminology associated with functional foods. Some contend that foods or ingredients attain functional status solely when produced through the integration of potentially beneficial substances derived from industrial byproducts and technological interventions or through the enrichment of these items with essential minerals [10].

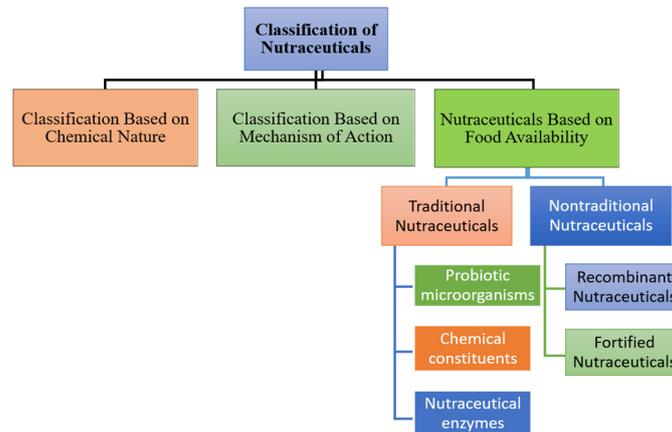


Figure 1. An overview of different types of nutraceuticals and their uses.

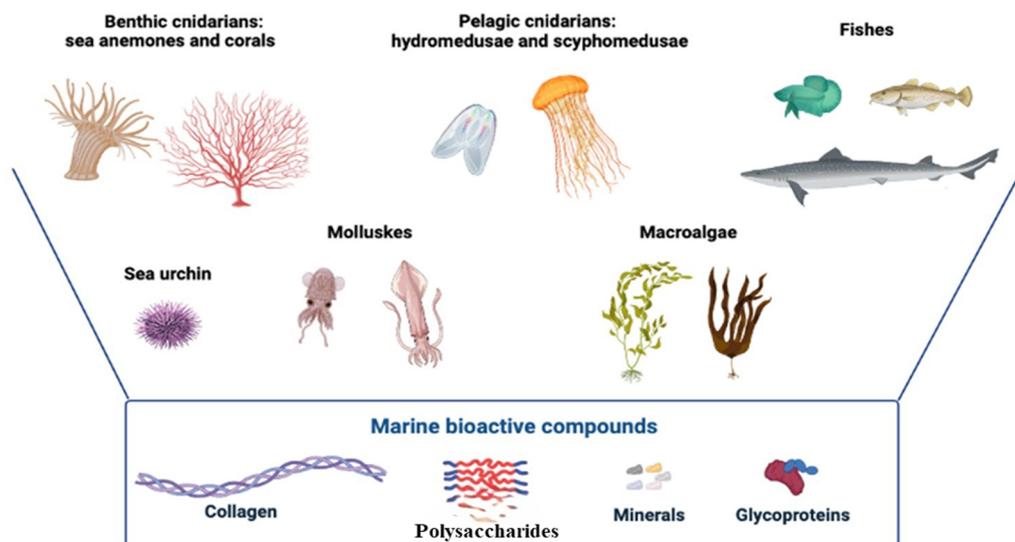


Figure 2. Main sources of marine bioactive compounds (collagen, polysaccharides, minerals, and glycoproteins): cnidarians, fish, mollusks, and microalgae, retrieved from [11].

Functional ingredients, which serve as vital constituents of the global food manufacturing sector, have witnessed significant growth since the 1980s. The market for these ingredients, especially those sourced from marine organisms, surpassed \$10 billion in 2018 and is projected to attain \$22 billion by 2025. Despite this growth, the absence of comprehensive global regulations complicates the definition of functional ingredients. These components are unique elements found in functional foods, contrasting with those in conventional foods or existing within them at substantially lower concentrations [12]. Functional ingredients, encompassing probiotics and probiotic supplements, omega-3 fatty acids, phospholipids, soluble fiber, herbal antioxidants, minerals, vitamins, proteins, peptides, and amino acids, can be systematically categorized based on their origin into three distinct classes: plant-derived ingredients, marine-derived ingredients, and microbial-derived ingredients.

Moreover, certain scholars continue to employ the phrase “prevention of diseases” even though functional foods neither effectively cure nor prevent health conditions [13]. Furthermore, a multitude of investigations document the application of functional foods or their components utilizing *in vitro* or animal-based methodologies [14],

while other studies conflate the distinctions between functional and conventional food products [15]. It is of paramount importance to elucidate that functional foods do not possess medicinal properties; they neither prevent nor treat ailments and should not be mistakenly identified with capsules, tablets, or any dietary supplementation. For a food product to be classified as functional, it is imperative that it undergoes rigorously validated intervention trials and adheres to the regulatory frameworks established by each sovereign nation. Within the context of a balanced diet, the fundamental criteria for categorizing functional foods or their components encompass safety, accessibility without the necessity of medical consultation, and a clear indication of health benefits [16]. It is crucial to disseminate knowledge regarding innovative functional ingredients, such as nutraceuticals, along with their progressive developments. A comprehensive understanding of the health implications associated with these ingredients will facilitate heightened awareness, foster health promotion, substantiate scientific claims, stimulate product innovation, and inform regulatory and policy-making efforts within this swiftly advancing domain. This review aspires to furnish an extensive examination of the functional ingredients utilized as nutraceuticals. It will investigate the most recent findings concerning the health advantages of these components, explore the technological advancements that augment their efficacy, and address the regulatory and safety considerations that are vital for their successful incorporation into the marketplace.

2. Marine-Derived Nutraceuticals

Nutraceuticals from marine sources encompass a wide array of bioactive compounds that confer substantial health advantages, such as antioxidant, anti-inflammatory, antidiabetic, anti-obesity, and anticancer (Figure 3). These nutraceuticals can be systematically categorized into various classifications, such as marine lipids, polysaccharides, and natural pigments, each exhibiting distinct therapeutic attributes. Omega-3 fatty acids, which are prevalent in fish oils and krill, are recognized for their anti-inflammatory and cardiovascular-promoting effects [17]. Krill oil is characterized by its content of astaxanthin and phospholipids, which augment bioavailability and deliver antioxidant benefits [18]. Algal polysaccharides, obtained from macroalgae, function as thickeners and stabilizers in food products while additionally serving as soluble dietary fibers [18]. Chitin and chitosan, derived from the exoskeletons of crustaceans, demonstrate cholesterol-lowering and weight-management efficacy [17]. These compounds disrupt the chain reaction of radical oxidation; chitosan and its derivatives possess antioxidant capabilities that offer protection against oxidative harm [19]. Carotenoids found in diverse marine organisms are endowed with antioxidant properties and may contribute to a reduction in cancer risk [20]. Although marine nutraceuticals exhibit considerable promise in enhancing health outcomes, their potential remains frequently underexploited due to obstacles related to sustainable sourcing and regulatory complexities. This situation underscores the necessity for continued research and development within this domain.

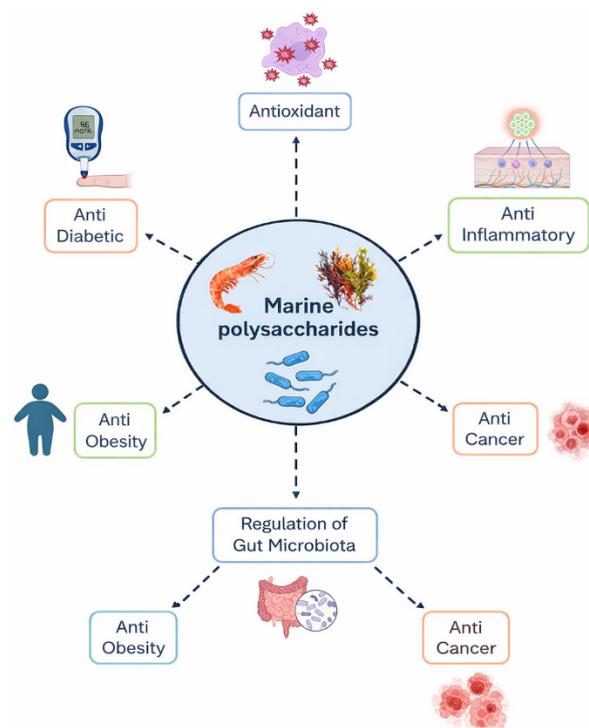


Figure 3. Marine-derived nutraceuticals and their major functions, retrieved from [21].

2.1. *Chlamydomonas Reinhardtii* as a Nutraceutical

One of the most thoroughly investigated microalgae species, *Chlamydomonas reinhardtii* (*C. reinhardtii*), has provided valuable insights into the photosynthetic and metabolic processes of eukaryotes and plants [22]. Studies on the effects of consuming whole *C. Reinhardtii* cells on the microbiota and gastrointestinal health in human volunteers have been studied. The results indicate that the consumption of *C. reinhardtii* cells can enhance the eubiosis of the microbiota, thereby reducing imbalances and enhancing overall intestinal health, even in situations where colitis stress has been induced [23]. Effective *in vitro* anticancer activity was demonstrated by the sulfated polysaccharides (SPs) derived from *C. reinhardtii* (Cr). With an IC₅₀ of 172 µg mL⁻¹, they specifically prevented the proliferation of triple-negative breast cancer cells (MDA-MB-231). These findings suggest that Cr-SPs identify promising areas for cancer therapy [24]. An investigation identified RPLKPW and AINPSK peptides from a transplastomic *C. reinhardtii* strain, demonstrating antihypertensive effects after intragastric administration to hypertensive rats [25]. These findings suggest that the strain can produce large amounts of antihypertensive peptides for functional food production. Oxidatively induced DNA base damage can be reduced to less than half of its magnitude by the carotenoid antioxidants lutein and neoxanthin, isolated from *C. reinhardtii*. In comparison with the control sample, the *C. reinhardtii* extract reduced approximately 76% of the damage [26]. We have summarized the recent clinical research and practice of nutraceuticals derived from microalgae in Table 1. Since the nutraceuticals derived from marine sources show plenty of health advantages, here we elaborate on the health benefits of marine nutraceuticals in detail.

Table 1. Biological properties of beneficial molecules derived from marine microalgae.

Beneficial Molecule (s)	Functional Ingredient (s)	Beneficial Effects on Human Health and Pharmaceutical Properties	Author (s)
Pigments (Carotenoids, Chlorophylls, and Phycobiliproteins)	Fucoxanthin, Astaxanthin, Lutein, Zeaxanthin	Anti-tumor, Anti-aging, Anti-inflammatory, Antiviral, Anti-cancer, Anti-obesity, Antioxidant, Anti-mutagenic, Anti-angiogenic, Anti-bacterial, Anti-diabetic, Anti-hypertensive, Anti-malarial	[20]
Polysaccharides	Alginate, Carrageenan, Fucooidan, Laminarin, Ulvan, Chitin, Chitosan,	Anti-tumor, Cardioprotective, Protease Inhibitor, Anti-inflammatory, Antiviral, Anti-thrombotic, Anti-cancer, Antioxidant, Immunomodulatory, Anti-bacterial, Anti-diabetic, Anti-hyperlipidemic, Anti-coagulant, Anti-allergic	[27]
Phenolic Compounds (Phenolic acids, Flavonoids, Phlorotannins)	Phenolic derivatives (Simple phenols, benzoic acid derivatives, phenylpropanoids, flavonoids, tannins, stilbenes, lignans, and lignins)	Antioxidant, Anti-cancer, Anti-bacterial, Anti-allergic, Antiproliferative, Anti-diabetic, Anti-inflammatory, Neuroprotective, Antifungal	[28,29]
Fatty acids	PUFA: ω-3 EPA and DHA, MUFA: ω-9 oleic acid, DHA ω-6 arachidonic acid, PUFA: ω-3 high/higher levels of EPA and DHA	Anti-cardiovascular, Anti-obesity, Anti-inflammatory, Anti-inflammatory properties, Prevention of mitochondrial dysfunction, Insulin resistance in skeletal muscle and neuronal cells, Reduction of the accumulation of visceral fat, Photoprotective properties, Prevention of erythema, Prevention of cardiovascular diseases, Improve the normal brain function and development, Anti-hypertensive, Prevention of adrenoleukodystrophy diseases, Regulation of blood cholesterol amounts, Promotion of heart health, Protection of the arteries walls, Promotion of cardiovascular health, Treatment of cutaneous infection, melanogenesis and dermatitis, Inhibition of bacterial infection (protection against <i>S. aureus</i>), Antioxidant properties, Immunomodulatory, Prevention of coronary heart diseases, Prevention of lymphoproliferative diseases, Treatment of diabetic conditions	[30,31]
Vitamins	Vitamin A, Vitamin D, Vitamin E	Antioxidant, Immunomodulatory, Anti-osteomalacia, Anti-rickets	[32]
Proteins	Essential Amino Acids (EAAs)	Treatment of diseases and conditions, Role in the mechanism of hormone secretion, Tissue repair, role in growth, protection of the myelin sheaths, Antioxidant, anti-obesity, and anti-inflammatory properties, Eliminates dangerous metals from the body, Metabolic regulation and modulation of the intestinal cell, Antibacterial an anticancer property, Modulation of gene expression, Antitumor, Antimicrobial, Regulation of neurological system, Prevention of cardiovascular disorders, Enhancing the immune system, The decrease of excessive body fat.	[33]
Mycosporine-like Amino Acids (MAAs) (Shinorine, palythenic acid, mycosporine-glycine, mycosporine-taurine, palythine, and Porphyra-334)	Unclear	Radical scavenging capacities and UV-absorbing capacities	[34]
Microalgal phyosterols	Unclear	Anticancer, antioxidative, anti-inflammatory, anti-atherogenicity, cardiovascular protection, and reduction in LDL cholesterol	[34]
Seaweeds	Polyphenols, polysaccharides, and sterols	Antioxidant, anti-inflammatory, anti-cancer, and anti-diabetic properties	[35]

2.2. Health Benefits

Nutraceuticals obtained from marine sources present a multitude of health benefits attributable to their abundant bioactive compounds. These compounds, encompassing omega-3 fatty acids, polysaccharides, and polyphenols, have undergone extensive investigation regarding their capacity to ameliorate a variety of health conditions. Marine-derived nutraceuticals, particularly those sourced from microalgae, demonstrate significant antioxidant activity. For instance, lutein derived from microalgae, particularly from the *Chlorella* genus, has garnered considerable attention due to its potent antioxidant and anticancer properties [36]. Foods rich in fucoxanthin have been shown to possess beneficial bioactive effects, including antibacterial, anticancer, antihypertensive, and antioxidant properties [37]. Prior research has attributed the extensive range of antioxidative characteristics of phycobiliproteins to their specific amino acid composition and the presence of double bonds within their chromophores [38].

Furthermore, a plethora of bioactive compounds exhibiting various antioxidant properties, including polyphenols, unsaturated lipids, peptides, sulfated polysaccharides, and amino acids, is found within the biochemical composition of seaweeds. Among the most notable compounds are fucoidans, carotenoids, and phlorotannins [39]. The antioxidant activity of chitosan, marketed as chitosamin[®], alongside surface-deacetylated chitin nanofibers (SDACNF), has also been documented [40]. Phlorotannins, which are polyphenolic secondary metabolites derived from specific seaweeds, as well as fucoidans, laminarans, and alginic acid polysaccharides isolated from brown algae, in addition to Sargachromanol E, extracted from *Sargassum horneri*, a species of brown algae, exhibit *in vitro* antioxidant properties, positioning them as promising candidates for application as potent antioxidants [35].

Marine nutraceuticals, specifically omega-3 fatty acids, are recognized for their capacity to decrease triglyceride concentrations and mitigate the risk of cardiovascular disease [41]. The incidence of coronary artery disease is associated with the reduced intake of marine fish and/or arctic mammals that are abundant in Ω -3 (or n-3) polyunsaturated fatty acids (PUFAs), notably eicosapentaenoic acid (EPA, 20:5 n-3) and docosahexaenoic acid (DHA, 22:6 n-3) [42]. Increased dietary fish consumption has been correlated with a reduced risk of cardiovascular disease (CVD) in individuals. Furthermore, in patients with lung cancer, fish oil supplementation has been found to increase chemotherapy efficiency [43]. After enzymatic treatment, peptides generated from fermented fish have also been found to be effective therapies for various cancers, viral infections, Alzheimer's disease, and hypertension [44]. The functional ingredients derived from various sources, particularly marine-derived foods, showed cardioprotective properties.

Further study is required to evaluate their bioavailability and the mode of action in detail. Investigations involving animal models have evidenced that fish proteins substantially lower serum cholesterol levels by delaying cholesterol absorption and bile acid synthesis. Additional health benefits attributable to fish proteins encompass their anti-obesity, anti-hypertensive, and anti-cancer properties. Omega-3 fatty acid-enriched fish oil has been shown to effectively reduce elevated triglyceride levels, a critical factor in the prevention of CVD, while also exhibiting anti-inflammatory, anti-depressive, and neuroprotective characteristics. Moreover, in patients diagnosed with lung cancer, supplementation with fish oil has been demonstrated to enhance the efficacy of chemotherapy [43].

Marine-derived polysaccharides and proteins display anti-inflammatory attributes, which may aid in the management of conditions such as arthritis and other inflammatory disorders [45] (Figure 4). These bioactive compounds also potentiate immune responses, thereby conferring a protective effect against infections [41]. Microalgal polysaccharides, which are categorized as pectins, glycoproteins, and sulfated polysaccharides (SPS), function as structural constituents, energy reserves, and protective agents. Among these polysaccharide categories, the sulfated group has been the focus of extensive research due to its anti-inflammatory properties [46]; notably, isolated polysaccharides from *Chlorella stigmatophora* and *Phaeodactylum tricorutum* demonstrated superior anti-inflammatory effects in rats subjected to carrageenan-induced paw edema when compared to the synthetic medication indomethacin [47]. A water-soluble 1,3-D-glucan extracted from the diatom was identified as chysolaminarin. When evaluated against human colon cancer cells, *Synedra acus* exhibited anti-proliferative effects [48]. Furthermore, microalgal fucoxanthin is being explored for its therapeutic potential in treating various inflammation-related conditions due to its potent antioxidant and microbiota-modulating properties [49]. The consumption of fish is linked to a significant potential for eliciting anti-inflammatory effects. Several investigations have utilized *in vitro* methods to evaluate these anti-inflammatory properties [50]. Nevertheless, tripeptides derived from salmon and hydrolysates obtained from tuna cooking liquid have manifested anti-inflammatory activity [51,52]. Porphyridium sulfated polysaccharide derived from microalgal extracts was shown to inhibit leukocyte migration to inflammatory sites *in vitro* [53].

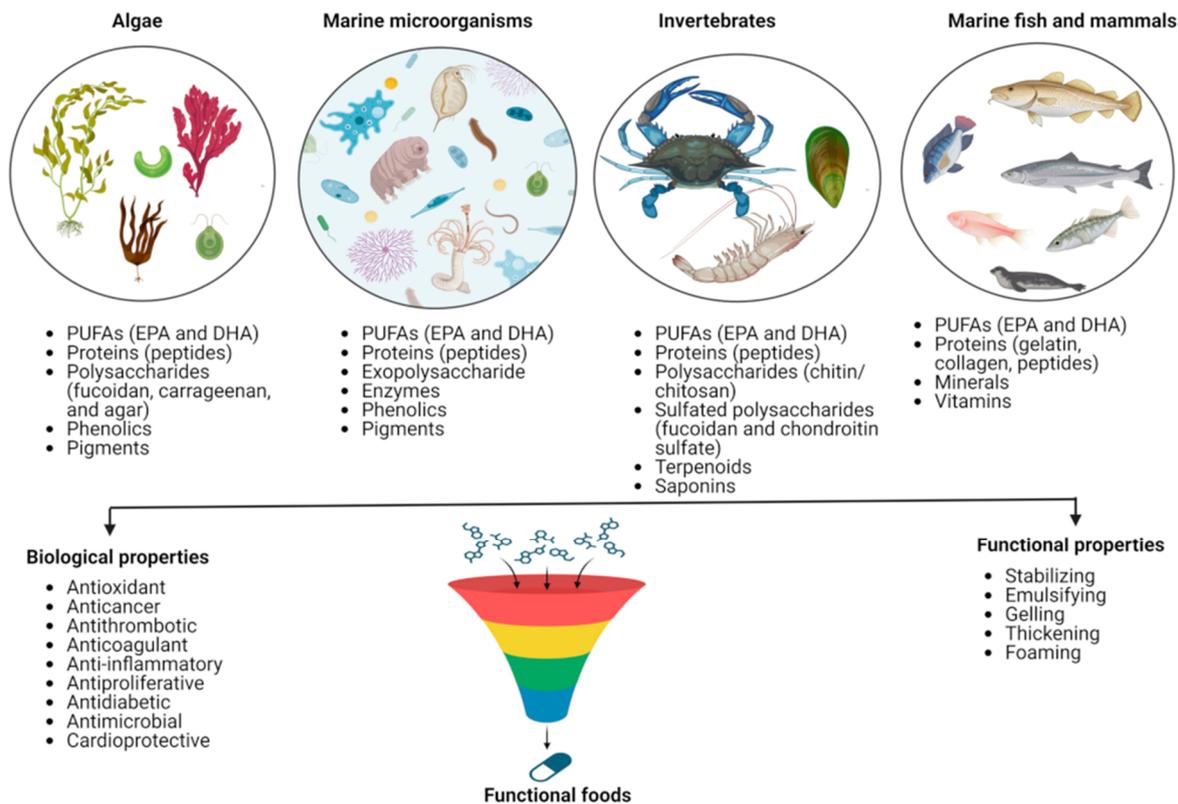


Figure 4. Overview of biological activities of marine-derived polysaccharides, retrieved from [54].

As the global community grapples with the impact of the novel coronavirus, the immune system's functionality emerges as a paramount determinant of an individual's health and well-being [55]. Regarding chitin and chitosan, studies indicate that the systemic delivery of chitin facilitates the macrophage-mediated release of cytokines. Additionally, it inhibits Th2 immunity while enhancing Th1 immunity. Empirical studies conducted *in vivo* have suggested that chitinase enzymes possess the capability to augment the immune response against infections [27]. Furthermore, another investigation revealed that laminaran exerted effective inhibition of human immunodeficiency virus (HIV) replication. It is capable of obstructing the function of HIV reverse transcriptase as well as the virus's ability to adhere to host cells [56]. An essential source of chitin and chitosan is derived from shell materials. The antibacterial efficacy of a biopolymer is positively correlated with the quantity of positively charged amino groups present within its molecular architecture. Chitosan exhibits superior antibacterial properties compared to chitin, attributable to its higher concentration of positively charged amino groups [57]. Microalgae have garnered considerable academic interest recently as a promising source for the sustainable synthesis of various bioactive compounds.

Among the bioactive substances identified in food additives and ingredients are phycobiliproteins, carotenoids, fatty acids, and vitamins [58]. Notably, research has demonstrated that microalgae can accumulate carotenes (α - and β -carotenes) and retinol, which serve as precursors of vitamin A and possess the capacity to inhibit the progression of certain cancers [59]. Evidence suggests that microalgal β -carotene serves as a more abundant source of 9-cis β -carotene compared to alternative sources. This structural composition largely contributes to its efficacy in scavenging free radicals [34]. Furthermore, the accumulation of vitamin D3 (cholecalciferol) in five distinct microalgae exposed to varying intensities of UVB radiation, along with the detection of vitamin B9 in powdered forms of *Chlorella* and *Nannochloropsis*, has also been documented. Notably, it has been concluded that a mere five grams of chlorella powder can fulfill five times the recommended daily allowance for vitamin B12 [60]. Consequently, through the modulation of the immune system, the regulation of gut microbiota, and the enhancement of the body's intrinsic anti-inflammatory and antioxidant mechanisms, the intake of novel functional components may contribute to a reduction in the incidence of chronic diseases.

Marine-derived nutraceuticals have demonstrated efficacy in regulating lipid profiles, glycemic control, and insulin resistance, rendering them advantageous for managing diabetes and obesity [61]. Nutraceuticals originating from marine sources, including krill and macroalgae, have exhibited significant effectiveness in managing lipid profiles, glycemia, and insulin resistance. These marine-derived compounds are abundant in bioactive constituents that confer various health benefits, particularly in the context of metabolic disorders. Recent findings indicate that

krill oil is effective in reducing triglyceride levels and enhancing cholesterol profiles, thereby favorably influencing lipid profiles. Additionally, macroalgae are characterized by polysaccharides that function as soluble dietary fibers, which may assist in regulating blood glucose levels and improving insulin sensitivity [18]. An investigation revealed that magnesium-rich deep seawater markedly improved insulin sensitivity and lipid profiles in subjects with compromised glucose tolerance [62]. A variety of marine bioactive compounds have been associated with the modulation of metabolic disorders, illustrating their potential applicability in nutraceutical development [63]. The lipid extract derived from blue mussels has been shown to significantly enhance glycemic parameters, diminish inflammatory cytokine levels, and favorably modify lipid profiles among Chinese patients with type 2 diabetes mellitus (T2DM), thereby indicating its effectiveness in the management of insulin resistance and lipid metabolism [64]. Research has indicated that extracts from *Sargassum compressa* and *Ecklonia arborea* demonstrate notable glycosidase inhibitory activity, implying their potential utility in regulating glycemia and insulin sensitivity, which is pertinent to the management of diabetes [65]. While marine nutraceuticals exhibit considerable promise in the regulation of metabolic health, it remains imperative to account for individual variability in responsiveness to these bioactive compounds. Additional investigation is warranted to comprehensively elucidate their long-term implications and optimal dosing strategies for diverse populations.

Nevertheless, among the more than 20,000 marine bioactive compounds that have been identified, only a limited fraction have undergone thorough investigation and application [20]. Numerous vital biological activities, including antihypertensive effects and antioxidant capabilities, have been substantiated by the myriad bioactive constituents extracted from algae, both *in vitro* and *in vivo*. These beneficial properties are intrinsically associated with the chemical composition of the respective peptides or carbohydrates. Various by-products and waste materials generated by the seafood processing sector, including shells, scales, tails, heads, and intestines, harbor valuable components. There has been a significant increase in interest regarding functional compounds derived from seafood in recent years. For example, researchers have identified approximately 2500 peptides sourced from marine flora that exhibit anti-proliferative effects [43]. While marine nutraceuticals offer substantial health advantages, it is crucial to acknowledge potential risks, such as heavy metal contamination in particular seafood varieties, which may negate their beneficial effects. Consequently, meticulous sourcing and consumption practices are essential for optimizing health benefits. Table 2 provides the health benefits of some prominent marine-derived nutraceuticals.

Table 2. Health Benefits of Nutraceuticals Derived from Marine Sources.

Type of Effects	Beneficial Compound (s)	Health-Promoting Effects	Author (s)
Antioxidant and anti-aging effects	Phlorotannins	<ul style="list-style-type: none"> • Anti-hyperlipidaemic and antihyperglycemic properties • Reduce the incidence of type 2 diabetes and cardiovascular disease because of their capacity to mediate hyperlipidemia and hyperglycemia 	[66]
	Spirulina's Phycocyanin	Anti-inflammatory, antiviral, antioxidant, hepatoprotective, and neuroprotective properties.	[67]
	Spirulina-derived proteins and pigments	Antihypertensive, antidiabetic, anti-obesity, and antioxidant	[68]
	Fish skin gelatin hydrolysate (FSGH)	High antioxidative activities	[69]
Cardiovascular Health	Fish oil	<ul style="list-style-type: none"> • Cardioprotective upsides reduce major coronary event incidence, improve cardiovascular risk, and lower the risk of stroke and coronary heart disease. • Regulate various signaling pathways, such as the nuclear factor kappa B pathway, the Toll-like receptor pathway, transforming growth factor-β (TGF-β) pathway, and peroxisome proliferators-activated receptor (PPAR) pathways. 	[70,71]
	Angiotensin-converting enzyme (ACE) inhibitory peptide (Gly-Leu-Pro) isolated from salmon (<i>Oncorhynchus keta</i>) and cod (<i>Gadus microcephalus</i>)	Significantly lower the systolic blood pressure in spontaneously hypertensive rats	[71]
	Phytochemicals	Anti-myocarditis substances	[72]
	<i>F. carica</i> methanolic extract from ripe fruits	Reduced heart rate, contraction force, and blood pressure in both normal and hypertensive rats	[73]
	<i>Chlorella ellipsoidea</i> Peptides	Suppression of the ACE-inhibitory activity	[74]

Table 2. Cont.

Type of Effects	Beneficial Compound (s)	Health-Promoting Effects	Author (s)
Metabolic Health (Diabetes and Obesity)	Chinese seaweeds, namely <i>Eucheuma spinosum</i> , <i>Grateloupia filicina</i> , <i>Ascophyllum nodosum</i> , and <i>Ulva pertusa</i>	• Prebiotic effects • Significantly enhanced <i>Bifidobacterium</i> proliferation	[75]
	Alginates in seaweeds	• Possess antiviral properties in animals and humans • In pigs, it reduces intestinal absorption of glucose and modulates insulin response.	[75]
	Zeaxanthin	Improving eye health and delaying the onset of malignancies such as breast cancer, pancreatic cancer, and type 2 diabetes	[76]
	Fish proteins (immunoglobulins)	Antiviral and Antibacterial infections prevent protein-calorie malnutrition.	[70]
Digestive Health	Three new derivatives of Schiffbase chitosan	Exhibited strong antimicrobial properties against gram-positive and gram-negative bacteria, including <i>Streptococcus mutans</i> and <i>E. coli</i> , as well as fungi, including <i>Aspergillus fumigatus</i> and <i>Candida albicans</i>	[77]
	Chitosan	Efficient reduction in the levels of triacylglycerol (TG) in the liver and plasma, as well as in the levels of total cholesterol (TC), LDL-C, and TG in the plasma	[78]
	Surface-deacetylated chitin nanofibers (SDCH-NF)	Stimulation of intestinal microbiota and plasma ATP enhanced the 5-HT levels.	[79]
Kidney Health	Carboxymethyl chitosan oligosaccharide	Regulating cytokines (IL-1 β , TNF- α , and TGF- β 1) and enhancing the expression of antioxidative enzymes (such as glutathione peroxidase and superoxide dismutase)	[80]
	Crude <i>Ganoderma applanatum</i> polysaccharide, polysaccharides extracted from <i>Cordyceps cicadae</i> , a polysaccharide from <i>Armillariella tabescens</i> mycelia, and <i>Ophiocordyceps lanpingensis</i> polysaccharide	Beneficial effects on the kidney	[81–84]
	Arginine, snakehead fish extract, and omega-3 polyunsaturated fatty acids	Powerful wound-healing properties	[50,85]
Other benefits	Fish PUFAs	Reduce cutaneous inflammation	[86]
	Chitosan and chitin	Antitumor activity, an inhibitory effect on the growth of MCF-7 breast cancer cells, and antiproliferative activity against HCT116 human colon cancer cells	[20]
	Tambjamines	antimicrobial, antitumorigenic, immunosuppressive, antiproliferative, and ichthyodeterrent activities	[87]

3. Mechanisms of Action

Recent investigations, supported by clinical data, aim to illuminate the mechanisms of action, safety, and efficacy of nutraceuticals. The forthcoming generation of therapeutic agents, which currently cannot be employed or endorsed as pharmaceuticals due to their ambiguous mechanisms of action, may encounter enhanced opportunities for utilization if their mechanisms are elucidated. Such agents may be instrumental in two primary areas: (1) the prevention of a constellation of conditions that may co-occur, including metabolic syndrome, management of inflammation, and Alzheimer's disease, and (2) the integration of pharmacological treatments, particularly for individuals who do not qualify for conventional pharmacological interventions. Over the preceding fifteen years, the exploration of the mechanisms of action of nutraceuticals has garnered more attention compared to the chemical assessment of food products aimed at demonstrating the presence of bioactive compounds. The mechanisms of action of nutraceuticals are multifarious, encompassing (1) modulation of gene expression; (2) modulation of cell signaling pathways; (3) gut microbiota interaction; (4) ROS/free radical scavenging and antioxidants; (5) mitochondrial homeostasis or mitochondria-targeting antioxidants; (6) anti-inflammatory; (7) anti-excitotoxic; (8) antiapoptotic and caspase inhibitor; and (9) metal chelation. These compounds, which are sourced from natural origins, exhibit a range of effects, such as antioxidant, anti-inflammatory, and neuroprotective properties, thereby rendering them valuable in the management of multifaceted diseases.

4. Application of Functional Ingredients as Nutraceuticals

A substance that is a food or a component of the food that has medical or health advantages, including the prevention and treatment of disease, was referred to as a nutraceutical in 1989. The term is formed from the words “nutrition” and “pharmaceutical”. Nutraceuticals are raw foods that are higher in bioactive molecules than their nutritional value and can be used as dietary supplements or functional food to improve overall health (treatment of disease and prevention) [20]. These can include the provision of functional foods or substances as well as the avoidance or management of illness. Nutraceuticals are substances that have powerful health-improving properties. Examples of these substances include vitamins, minerals, and vital fatty acids. They can prolong life, slow aging, fend against chronic illnesses, and/or enhance the body’s structure and/or function. Nutraceuticals are attracting much attention due to their high nutritional qualities, medicinal effects, and relative safety.

Nutraceuticals are used in medical specialties for preventive purposes due to their therapeutic benefits [33]. Fish and fisheries byproducts are a significant source of nutraceuticals, including long-chain PUFAs, omega-3 PUFAs, peptides, and vitamins. Recently, immunomodulatory peptides have been discovered, which can be used as adjuvants in vaccines and as active ingredients in drug design [88]. Microalgae, including seaweed, are a valuable source of therapeutic compounds with therapeutic properties. These compounds are used in nutraceuticals and functional foods due to their biocompatibility and availability [89]. Chitosan, a safe dietary supplement, can improve human health by reducing disease incidence. Marine invertebrates, such as mollusks and crabs, have been used as sources of organic-based biopolymers, including chitin, chitosan, glycosaminoglycans, and fucosylated chondroitin sulfate, which have shown potential in treating various diseases and are also used in animal feed [90]. Marine animal-derived ingredients like collagen and gelatin are used in biomedical applications. Sponges contain bioactive compounds, including sterols with anti-microbial properties. The *Plexaura hamomala* is the richest source of prostaglandins. Marine polychaete treats various disorders. Shrimp fats, rich in free fatty acids, triglycerides, and carotenoids, have potential health benefits in muscle and exoskeleton. Marine animal-derived ingredients like collagen and gelatin are used in biomedical applications [91]. Sponges contain bioactive compounds, including sterols with anti-microbial properties. The *Plexaura hamomala* is the richest source of prostaglandins. Marine polychaete treats various disorders [92]. Shrimp fats, rich in free fatty acids, triglycerides, and carotenoids, have potential health benefits in muscle and exoskeleton [93]. Marine polysaccharides, such as sulfated galactans and fucans, have gained interest due to their pharmacological and nutraceutical properties [27,94]. They can be used in nutraceuticals and functional foods due to their anticoagulant properties [95]. Biopolymers from shellfish waste, such as scallops, cockles, and mussels, can be used as dietary supplements and animal feed. Carrageenan, furcellaran, and exopolysaccharides from marine cyanobacteria are also used in the food industry [96]. Agar, a primary source of exopolysaccharides, has been used in the food sector for food gums, gel formation, and additives. Chitoooligosaccharide (COS) and astaxanthin-rich microalgae have the potential for use in functional food development due to their antioxidant activity [97].

Forms of Application of Functional Ingredients in Nutraceuticals

Nutraceuticals are used in medical specialties for preventive purposes due to their therapeutic benefits [33]. Fish and fisheries byproducts are a significant source of nutraceuticals, including long-chain PUFAs, omega-3 PUFAs, peptides, and vitamins. Carrots contain high concentrations of nutraceuticals, making them beneficial foods [98]. Recently, immunomodulatory peptides have been discovered, which can be used as adjuvants in vaccines and as active ingredients in drug design [88]. Plant-based peptides, like defensins, have immunomodulatory and antimicrobial effects, making them ideal for functional food and feed preparation. Argan pulp, a by-product of the argan oil industry, has health-promoting effects and potential for nutraceutical formulation [99]. Microalgae, including seaweed, are a valuable source of therapeutic compounds with therapeutic properties. These compounds are used in nutraceuticals and functional foods due to their biocompatibility and availability [89]. Chitosan, a safe dietary supplement, can improve human health by reducing disease incidence. Marine invertebrates, such as mollusks and crabs, have been used as sources of organic-based biopolymers, including chitin, chitosan, glycosaminoglycans, and fucosylated chondroitin sulfate, which have shown potential in treating various diseases and are also used in animal feed [90]. Marine animal-derived ingredients like collagen and gelatin are used in biomedical applications. Sponges contain bioactive compounds, including sterols with anti-microbial properties. The *Plexaura hamomala* is the richest source of prostaglandins. Marine polychaete treats various disorders. Shrimp fats, rich in free fatty acids, triglycerides, and carotenoids, have potential health benefits in muscle and exoskeleton. Carotenoids and PUFAs have been studied for cancer prevention in both lab and animal research. Marine animal-derived ingredients like collagen and gelatin are used in biomedical applications [91]. Sponges contain bioactive compounds, including sterols with anti-microbial properties. The *Plexaura hamomala*

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5. Challenges and Future Directions

Nutraceuticals' efficacy in prevention and therapy is hindered by a lack of clinical data, preventing their use on health claims. Bioavailability, which depends on food composition, affects their efficacy. Barriers to their effective distribution include chemical instability during digestion, poor solubility, slow absorption, and first-pass metabolism [100]. Nutraceutical delivery is challenging for producers, with systems like nanoparticles, intestinal permeation enhancers, and mucolytics being studied. New delivery systems, such as oil-water emulsions, core-shell nanoparticle delivery systems, nanoencapsulation, and nanoemulsions, have been suggested [101]. However, legal and regulatory challenges remain, such as the potential use of cocoa flavonoids as nutraceuticals and the combination of statin with cholesterol-lowering nutraceuticals [102]. Nutraceuticals are categorized as food supplements, leading to confusion among consumers and a lack of proper market information. Nutraceuticals, derived from foodstuffs, often lack a proper assessment of their health effects. In the USA, the FDA focuses on the safety aspects of food supplements, acknowledging the term nutraceutical. Manufacturers are responsible for ensuring a product is safe before it is released. There is no need for FDA registration, and health claims and nutrient content claims can be authorized on food labeling if authorized by the Academy of Sciences or other federal authorities [103].

In summary, nutraceuticals derived from marine sources pose special scientific, technological, and regulatory challenges. These challenges include variations in bioactive composition caused by seasonal and environmental factors, oxidative degradation susceptibility, risks of heavy metal and persistent pollutant contamination, limited bioavailability and clinical validation, complicated extraction and standardization procedures, sustainability concerns related to overexploitation of marine resources, and problems with consumer acceptance and global regulatory harmonization.

Research Gaps and Scientific Validation

Functional substances have the potential to improve human nutrition, but safety concerns remain. Microalgal-based products face limitations, including a lack of information on effectiveness and safety, the presence of mycotoxins, pesticides, heavy metals, and allergies. In-depth studies on allergic chemicals are needed, and regulatory agencies must emphasize the potential consequences of microalgal-based food labeling. Toxins produced by microalgae, such as microcystin and anatoxin, can harm the liver, digestive system, and nerve axon function. Challenges include accessibility, availability, sustainable metabolite removal methods, preservation, bioavailability, and food product safety and sensory quality [104]. Fish has therapeutic benefits and health benefits, but there is uncertainty about toxicological and environmental risks. Toxicants, price, availability, social values, religion, cultural impact, and education make eating fish challenging. The Dietary Guidelines for Americans recommend 8 ounces of seafood per week, with women pregnant or nursing women consuming 8-12 ounces of a variety lower in mercury. Mercury levels are minimal in salmon, pollock, shrimp, light tuna, and catfish [33]. Insufficient clinical trials have limited research on the toxicity profile of phytochemicals, such as colchicine, which causes splenic apoptosis and increases neutrophil counts in mice [72]. Maize bioactive peptides have shown biological effects but no solid evidence of effectiveness in humans [105]. Clinical trials using functional ingredients/foods provide valuable information, but there are challenges compared to conventional drug trials [106]. Nutraceuticals *Turnera subulata* and *Harpagophytum procumbens* may be effective in treating neurological disorders, but more research is needed [107].

6. Future Perspective and Conclusions

Over the past two decades, researchers have been exploring the development of functional foods that can provide health benefits for chronic diseases and meet the nutritional needs of conventional diets [15]. In Japan, functional foods have been shown to increase nitric oxide synthesis and reduce the risk of cardiovascular disease and salt-induced hypertension [108]. Further research is needed to optimize the Quorn fermentation process for sustainable, functional ingredients [34]. The food industry uses whole microalgal biomass or their extracted compounds as ingredients in various food products [109]. Seaweed, particularly bioactive peptides and carbohydrates, is a promising source of novel compounds for functional foods and nutraceuticals [110]. *Anoectochilus burmannicus* extract (ABE) has potential as a stabilizer for nanoparticles, supporting the development of ABE-SeNPs stabilizers for nano-selenium as a food supplement or functional ingredient with health benefits [111]. Mycosporine-like amino acids (MAAs) as natural food preservatives are hypothesized for their ability to scavenge free radicals.

The prospective trajectory of nutraceuticals originating from botanical, marine, and microbial origins appears highly favorable, with numerous pivotal trends and advancements anticipated to influence the overall domain. A continuous scholarly investigation is projected to augment our comprehension of the bioactive constituents present within these sources. Technological innovations, including genomics and metabolomics, are expected to elucidate novel nutraceuticals and their associated health advantages. As the knowledge about individual genetic and metabolic profiles advances, the nutraceutical market may transition towards personalized supplements designed to address specific health requirements, potentially enhancing efficacy while mitigating adverse effects. There is an increasing focus on sustainable methodologies in procuring marine and plant-derived nutraceuticals. Enterprises may progressively emphasize ethical resource management and biodiversity, thereby fostering the creation of environmentally conscious products. Heightened scrutiny from regulatory agencies may result in more rigorous guidelines concerning the efficacy and safety of nutraceuticals. This development could enhance consumer trust; however, it may simultaneously pose challenges for manufacturers. Nutraceuticals may become more seamlessly integrated into conventional healthcare practices, with healthcare professionals increasingly advocating for their use as adjunctive therapies in conjunction with traditional treatments. Progress in delivery modalities, such as nanotechnology or microencapsulation, has the potential to enhance the bioavailability and stability of nutraceuticals, thereby augmenting their therapeutic impacts. As awareness regarding the health benefits of natural products escalates, the global market for nutraceuticals is poised for expansion, providing opportunities for enterprises and researchers across the globe.

Nutraceuticals derived from botanical, marine, and microbial sources exhibit considerable promise for enhancing health and addressing disease management. Comprehensive research endeavors persist in unveiling their prospective advantages, encompassing anti-inflammatory and antioxidant properties as well as influences on gastrointestinal health and immune function. As the understanding of these extraordinary substances deepens, their significance within public health initiatives is expected to amplify correspondingly. Nevertheless, the efficacious incorporation of nutraceuticals into health regimens necessitates meticulous scientific validation and adherence to regulatory benchmarks. The emphasis on sustainable sourcing practices is poised to play an instrumental role in guaranteeing the continued viability of these resources for forthcoming generations. Ultimately, the future of nutraceuticals is entrenched in a holistic paradigm of health, accentuating prevention, wellness, and a reconnection with nature as therapeutic avenues. Ongoing innovation and research are likely to yield novel insights that enhance our understanding of leveraging nature's power to achieve improved health outcomes.

Conflicts of Interest

The author declares no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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