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Review

From Marine Algal Bioactives to Scalable Applications: Integrating Extraction, Mechanisms, Delivery, Safety, and Commercial Translation

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Abstract

Marine algae are emerging as important biological resources for the discovery and development of bioactive compounds with applications across food, pharmaceutical, cosmetic, agricultural, aquaculture, environmental, and biotechnological systems. This review critically synthesizes current knowledge on macroalgae and microalgae as sources of sulfated polysaccharides, carotenoids, phenolic compounds, proteins, peptides, vitamins, mycosporine-like amino acids, and polyunsaturated fatty acids. Emphasis is placed on the relationship between algal source, cultivation conditions, compound structure, extraction strategy, formulation, and biological activity. Key mechanisms of action are discussed, including antioxidant defense, modulation of inflammatory signaling, inhibition of metabolic enzymes, antimicrobial and antiviral activity, interactions with the gut microbiota, and regulation of cell-cycle-related pathways. Recent progress in biotechnological production, green extraction, purification, analytical characterization, bioaccessibility, bioavailability, and delivery systems is evaluated in the context of real product development. The review further highlights the use of algal bioactives in functional foods, nutraceuticals, pharmaceuticals, cosmeceuticals, aquafeeds, crop biostimulants, and environmental remediation. Current limitations, including biomass variability, compound instability, limited human validation, regulatory complexity, safety concerns, and scale-up costs, are also addressed. Overall, marine algae provide a sustainable and multifunctional platform for developing bioactive products when discovery, processing, validation, and commercialization are integrated.

Keywords: macroalgae; seaweed; microalgae; secondary metabolites; algal biotechnology; functional foods; nutraceuticals; biorefinery

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1. Introduction

Ocean environments cover approximately 70% of the Earth's surface and host remarkable biological diversity, making them major reservoirs for the discovery of bioactive natural products with applications in medicine, food systems, and biotechnology [1–3]. The identification of spongothymidine in 1945 as the first biologically active compound obtained from a marine source marked the beginning of marine natural product research, which has since led to the discovery of more than 39,500 compounds with diverse biological activities [4]. Marine organisms are widely recognized as prolific producers of secondary metabolites that mediate ecological functions such as defense, communication, antifouling, and toxicity, reflecting biochemical adaptations to selective pressures in marine environments; within

this broader chemical diversity, marine algae have emerged as important sources of bioactive compounds with expanding relevance across pharmaceutical, nutraceutical, cosmetic, and food sectors [3,5]. Recent work on common marine traditional Chinese medicine further supports the pharmacological relevance of marine-derived resources by summarizing anti-inflammatory, antioxidant, antitumor, antiviral, immunomodulatory, and metabolic regulatory activities, many of which are linked to polysaccharides, terpenoids, sterols, alkaloids, and other marine natural products [6]. Marine algal resources are increasingly described as chemically diverse yet underutilized, with both macroalgae and microalgae producing a wide spectrum of metabolites, including sulfated polysaccharides, carotenoids, polyphenols, sterols, proteins and peptides, and lipid fractions rich in polyunsaturated fatty acids (PUFAs) [1,7]. Representative compounds such as fucoidan, alginate, carrageenan, ulvan, fucoxanthin, astaxanthin, and phlorotannins are widely reported in marine algae, and studies have shown that these classes of metabolites collectively exhibit a range of biological activities, including antioxidant, anti-inflammatory, antimicrobial, antiviral, anticancer, metabolic, and skin-related effects, depending on compound structure and source [7–9]. These functional properties have driven growing interest in marine algal bioactives for pharmaceutical, nutraceutical, functional food, and cosmetic applications [1,8].

Beyond compound identification, current research increasingly emphasizes the practical utilization of marine algal bioactives, particularly through improved extraction processes, integrated biorefinery approaches, and production strategies that enhance the feasibility of industrial applications [10,11]. Recent studies indicate that the extraction of marine algal bioactives is shifting toward greener, more effective technologies, and that biorefinery processes are being explored to enable fuller biomass valorization and improve environmental sustainability [11]. This shift is critical because the commercial translation of marine algal bioactives depends not only on biological activity, but also on efficient extraction, compound stability, product quality and safety, and the feasibility of large-scale processing [12]. Current evidence indicates that promising bioactivity alone is insufficient for practical application. For example, recent work on Ulva-derived bioactives demonstrates that low chemical stability, poor oral bioavailability, and undesirable sensory properties can significantly limit practical use, underscoring the need for advanced processing methods, such as encapsulation, to preserve bioactivity and enhance application potential [13]. Broader reviews likewise highlight continuing challenges related to standardization, variability in composition and processing, safety assessment, and regulatory acceptance for algae-derived products intended for food and health-related applications [8,14].

Against this background, this review examines marine algae as strategic sources of bioactive compounds and natural products, with emphasis on major compound classes, mechanisms of action, and applications in food, pharmaceutical, nutraceutical, cosmetic, agricultural, aquaculture, environmental, and biotechnological contexts. Attention is given to extraction strategies, processing and formulation considerations, bioaccessibility, bioavailability, safety, regulation, and the practical barriers that still limit wider commercialization, including compound instability, limited validation, regulatory complexity, and scalable production. By connecting compound-level functionality with processing, validation, safety, and industrial applicability, this review provides an integrated, application-oriented perspective on the potential of marine algae as platforms for developing high-value, scalable, and commercially realistic bioactive products.

2. Materials and Methods

2.1. Literature Selection, Scope, and Review Positioning

This review was developed as a structured narrative synthesis of marine algal bioactives, with emphasis on the pathway from algal source and compound recovery to mechanisms of

action, product formulation, safety, regulation, biorefinery development, and commercial translation. The literature search focused primarily on peer-reviewed articles and authoritative institutional reports published between 2016 and 2026, with selected earlier studies included when they provided essential historical, mechanistic, toxicological, regulatory, or techno-economic context. Searches were conducted using Web of Science, Scopus, PubMed, ScienceDirect, Google Scholar, MDPI, SpringerLink, Frontiers, Wiley Online Library, and official institutional sources. Search terms were applied individually and in combination using Boolean operators and included "marine algae bioactive compounds," "marine algal metabolites," "seaweed bioactives," "macroalgae bioactive compounds," "microalgae bioactive compounds," "marine polysaccharides," "algal pigments," "phlorotannins," "polyunsaturated fatty acids," "green extraction," "bioavailability," "delivery systems," "toxicity," "regulation," "biorefinery," "techno-economic analysis," and "commercialization."

Retrieved publications were screened by title, abstract, and full text for relevance to marine algal sources, bioactive compound classes, extraction and characterization methods, biological mechanisms, application potential, safety, scalability, and economic feasibility. Inclusion criteria prioritized peer-reviewed original research articles, review articles, clinical and preclinical studies, analytical and processing studies, techno-economic and life-cycle assessments, regulatory documents, and authoritative institutional reports directly relevant to marine macroalgae, microalgae, or marine algal bioactive compounds. Exclusion criteria included studies focused solely on freshwater algae and unrelated to marine algal systems; publications lacking clear methodological or compositional information; non-peer-reviewed sources without institutional authority; duplicate records; and articles unrelated to extraction, bioactivity, formulation, safety, regulation, biorefinery design, or commercial translation.

Previous reviews have addressed important areas of marine algal bioactive research, including broad health and nutraceutical applications of marine algae, microalgal bioactives, macroalgal bioactives, seaweed extraction technologies, marine polysaccharides, algal pigments, phenolic compounds, phlorotannins, proteins, lipids, delivery systems, functional foods, safety, regulation, and algal biorefineries [1,7,8,10–36]. However, many of these reviews are organized around a single algal group, compound class, biological activity, processing method, product sector, or industrial pathway rather than the complete development sequence from biomass sourcing to commercial translation [1,10,12,18–20,23–25,29,31,32,35]. The present review differs in that it integrates macroalgal and microalgal sources with biomass generation, extraction, and characterization; structure-related mechanisms of action; bioaccessibility; delivery systems; safety; regulation; techno-economic analysis; and commercial translation within a single application-oriented framework. This organization is intended to clarify not only the reported biological potential of marine algal bioactives but also the processing, validation, safety, regulatory, and scale-up requirements needed to move them from discovery-stage research into reproducible, safe, and commercially realistic products.

Accordingly, evidence was synthesized with emphasis on relationships among extraction techniques, metabolite structure, biological mechanisms, application relevance, and translational limitations, including stability, bioavailability, safety, regulatory, and scale-up challenges [11,12,23–28,30,32,37–39].

2.2. Preparation of Graphical Illustrations

The graphical abstract and schematic figures were created by the authors using BioRender. ChatGPT (OpenAI) was used to assist with visual polishing, layout refinement, formatting, and improvement of graphical clarity and readability. The scientific content, conceptual design, interpretation, and final approval of all graphical materials were completed by the authors.

3. Marine Algae as Sources of Bioactive Compounds

Marine algae are broadly categorized into microalgae and macroalgae, which differ in biological organization, biomass structure, production characteristics, and dominant bioactive profiles. Marine microalgae are microscopic photosynthetic microorganisms, including eukaryotic microalgae and cyanobacteria, that synthesize a wide range of metabolites, including PUFAs, carotenoids, phycobiliproteins, peptides, sterols, polysaccharides, phenolic compounds, vitamins, and mycosporine-like amino acids (MAAs), many of which have been associated with health-promoting and industrial applications [1,7,35]. In contrast, marine macroalgae, or seaweeds, are multicellular macroscopic algae commonly classified into green algae (Chlorophyta), red algae (Rhodophyta), and brown algae (Phaeophyceae), with this grouping reflecting differences in pigmentation, biochemical composition, metabolite profiles, and dominant polysaccharides [7,12]. These macroalgal groups contain proteins, pigments, polyphenols, fatty acids, vitamins, minerals, and structurally distinct polysaccharides, with brown algae widely described as sources of fucoidan and alginate, red algae as sources of carrageenan and agar, and green algae as sources of ulvan and related sulfated polysaccharides [7,12]. In addition to these major compounds, marine macroalgae also produce pigments, rare sugars, oligosaccharides, and other high-value metabolites that are increasingly explored for food, pharmaceutical, nutraceutical, and cosmetic applications [12].

4. Biotechnological Production and Biomass Generation of Marine Algal Bioactives

Marine algae function as biotechnological production platforms because microalgae and macroalgae synthesize structurally diverse bioactive compounds, including proteins, lipids, polysaccharides, pigments, phenolic compounds, peptides, and other secondary metabolites with applications in food, pharmaceuticals, nutraceuticals, cosmetics, and the environment [18,36]. The production of marine algal bioactives is not only determined by algal species but also by cultivation design, environmental control, stress induction, harvesting strategy, downstream processing, and product stabilization [40,41]. For this reason, cultivation should be considered an upstream bioprocessing step that directly influences biomass productivity, metabolite concentration, extractability, and commercial feasibility [20,42].

Microalgal production systems are strongly influenced by strain selection and culture conditions because light, salinity, nutrient availability, carbon supply, temperature, and growth phase can alter both biomass accumulation and biochemical composition [40,43,44]. Light is a central cultivation parameter because light intensity, photoperiod, and spectral quality affect photosynthesis, growth, pigment synthesis, fatty acid production, and overall metabolite productivity in microalgal cultures [43,44]. Nutrient regulation is also important because nitrogen availability can shift the balance among protein, lipid, and fatty acid accumulation in microalgae, as shown in *Nannochloropsis gaditana* biomass enriched in eicosapentaenoic acid (EPA) and protein through sodium nitrate supplementation [45]. Salinity stress has also been reported to influence microalgal metabolism, as changes in osmotic pressure and ion concentrations can alter pigment accumulation, fatty acid composition, antioxidant responses, and cell membrane properties [43]. Targeted stress induction is one of the main biotechnological strategies used to enhance the accumulation of selected marine algal bioactives because abiotic stress can stimulate the production of pigments, antioxidant compounds, phenolic compounds, polysaccharides, and PUFAs [43,46]. A two-stage cultivation strategy is particularly useful because the first stage can be used to generate biomass under favorable conditions, while the second stage can expose cells to controlled stress conditions that stimulate metabolite accumulation [43]. In *Tetraselmis tetrathele*, two-stage cultivation in food wastewater followed by salinity and light stress increased pigment

content and antioxidant capacity, with the highest pigment content reported under 40 g L^{-1} salinity stress with fluorescent light [43]. In the same study, the lowest 2,2′-azinobis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) IC50 value was observed in ethanol extracts from cultures exposed to red LED light stress at 300 µmol m^{-2} s^{-1}, while the highest ferric reducing antioxidant power (FRAP) value was reported in ethanol extracts from cultures exposed to salinity stress under fluorescent light.

Nutrient regulation and downstream cell disruption can also be integrated to improve the production and application of marine microalgal bioactives [45]. In *Nannochloropsis gaditana*, sodium nitrate supplementation at 1.76 mmol L^{-1} enabled co-enrichment of EPA and protein in the dry biomass, supporting the development of EPA-rich emulsions from the same algal material [45]. The same study showed that high-pressure microfluidization released more soluble protein, lipids, and EPA than ultrasonication and bead milling, suggesting that the cell-disruption method can affect the recovery and functional performance of marine microalgal compounds. In vitro digestion further confirmed improved EPA bioaccessibility in emulsions prepared by high-pressure microfluidization and ultrasonication, indicating that cultivation and processing strategies must be aligned with the intended product format [45].

Photobioreactor design is another important factor in the biotechnological production of marine microalgal bioactives because reactor geometry and operating conditions influence light utilization, mass transfer, nutrient delivery, biomass productivity, biochemical yield, and scalability [40]. Hashmi et al. [40] compared tubular, flat-panel, vertical-column, hybrid, and membrane-integrated photobioreactors and reported that each design involves trade-offs among productivity, energy demand, fouling, oxygen accumulation, and operational feasibility. Deprá et al. [44] also reported that photobioreactors can improve the control of microalgal cultivation, but large-scale implementation remains limited by technical and operational barriers. Light attenuation in dense algal cultures can create internal light gradients, reducing photosynthetic efficiency and underscoring the importance of reactor design, mixing, surface area-to-volume ratio, and material selection for maintaining productivity. Emerging strategies such as LED-based spectral control, modular hybrid systems, membrane-assisted biomass retention, computational fluid dynamics, and image-based monitoring have been proposed to improve reactor performance and contamination control, but their industrial value depends on cost, energy use, and local production conditions [40].

Macroalgae require a different production framework because their commercial value is linked to biomass availability, species composition, harvesting strategy, seasonal variability, and fractionation into multiple product streams [18,19,42]. Macroalgae are considered promising feedstocks for biorefinery development because they can provide carrageenan, alginate, proteins, lipids, pigments, biostimulants, bioactive extracts, and bioenergy products from a single biomass source [18,19]. Arias et al. [18] reported that the economic viability of macroalgal biorefineries depends on production yield, resource demand, and the ability to scale up green extraction technologies to full-scale operation. Ferreira et al. [42] showed that wild kelps, cultivated *Macrocystis pyrifera*, and industrial residual pulp contained proteins, fatty acids, polyphenols, and antioxidant activity, supporting the use of both primary biomass and processing residues for blue biotechnology applications. The biochemical profile of seaweed depends on taxon, geographical location, harvesting season, environmental factors, cultivation conditions, life cycle stage, and processing method, which means that standardized production and characterization are necessary for consistent bioactive compound recovery [42].

Biorefinery design is essential to improving the feasibility of marine algal bioactive production because single-product algal systems often face economic limitations, while multiproduct recovery can spread costs across several high-value fractions [18,20,42].

Closed-loop microalgal biorefineries can reduce the environmental and energy burdens associated with standalone biofuel production by integrating the recovery of high-value bioproducts [20]. Large-scale microalgal biorefineries face major challenges in harvesting and processing because these stages are costly and energy-intensive [42]. Alqahtani [41] also emphasized that extraction efficiency, product stability, solvent management, energy intensity, quality assurance, and regulatory compliance determine whether microalgal high-value products can move from biological potential to industrial application.

5. Bioactive Composition of Marine Algae

Marine algae are reported to contain diverse classes of bioactive compounds, including polysaccharides, proteins, pigments, polyphenols, fatty acids, vitamins, and minerals, which underscore their relevance as sources of functional and nutraceutical ingredients [7]. Marine microalgae synthesize several major classes of bioactive compounds, including PUFAs, carotenoids, phycobiliproteins, peptides, sterols, polysaccharides, phenolic compounds, vitamins, mycosporine-like amino acids (MAAs), and alkaloids [35]. Marine macroalgae are also considered versatile biomass resources capable of producing high-value compounds, including pigments, rare sugars, sulfated polysaccharides, and oligosaccharides, for pharmaceutical, nutraceutical, and cosmetic applications [12]. In addition to their basic nutritional components, algae are also reported to produce a wide range of secondary metabolites that contribute to their functional properties and industrial relevance [47,48]. These compounds include a variety of pigments, antioxidants, and unique phytochemicals with health-promoting properties [48]. Algal pigments such as chlorophyll, carotenoids, and phycobiliproteins are not only responsible for the vibrant green, red, and blue hues of different algae but also exhibit significant nutritional, medicinal, and antioxidant properties [49]. For instance, *Arthrospira platensis* Gomont, formerly known as the synonym *Spirulina platensis* (Gomont) Geitler, according to AlgaeBase, contains the blue protein pigment C-phycocyanin, which exhibits potent antioxidant and neuroprotective effects by enhancing endogenous antioxidant enzyme activity and suppressing key inflammatory mediators [35]. For marine algal polysaccharides, structural features such as sulfation pattern, monosaccharide composition, branching, and molecular weight have been reported to influence physicochemical properties and biological activity [17]. Marine algal species, key bioactive compounds, and reported biological or biotechnological relevance are summarized in Table 1.

Table 1. Marine algal species, key bioactive compounds, and reported biological or biotechnological relevance.

Algal Species	Group	Bioactive Compound(s)	Function	Reference
Limnospira platensis/ (*Arthrospira platensis*)	Microalga/ cyanobacterium	Proteins, phycocyanin, gamma linolenic acid (GLA)	Used in supplements, functional foods, protein powders, and snacks	[35]
Chlorella vulgaris	Microalga	Protein, chlorophyll, vitamin B12	Used in supplements for detoxification and immune support	[35]
Haematococcus pluvialis	Microalga	Astaxanthin	Antioxidant, anti-aging, and cardiovascular protection	[35]
Nannochloropsis gaditana	Microalga	Eicosapentaenoic acid (EPA), protein	Sustainable alternative to fish oil for omega-3 supplementation; reduced inflammation and liver fibrosis markers in rats	[45]

Table 1. *Cont.*

Algal Species	Group	Bioactive Compound(s)	Function	Reference
Nannochloropsis oceanica	Microalga	EPA-rich biomass	Alternative to fish oil: reduced inflammation markers in rats	[50]
Scenedesmus almeriensis	Microalga	Lutein	Used in supplements and functional foods for eye health and antioxidant support	[35]
Tetraselmis suecica	Microalga	Phytosterols, lutein, carotenoids	Supports cholesterol balance and ocular health	[35]
Euglena gracilis	Microalga	Paramylon (β 1,3-glucan)	Immunomodulatory and metabolic regulatory effects	[51]
Phaeodactylum tricornutum	Microalga	Fucoxanthin	Improved cognitive function in older adults with self-perceived cognitive decline	[52]
Isochrysis galbana	Microalga	Docosahexaenoic acid (DHA) and EPA-rich biomass/lipid extract	Used to formulate yogurt enriched in omega-3 long-chain polyunsaturated fatty acids (PUFAs)	[53]
Fucus vesiculosus	Brown macroalga	Phlorotannins	Antioxidant, anti-diabetic, and anti-obesity effects	[54]
Ascophyllum nodosum	Brown macroalga	Phlorotannins/ polyphenols	Inhibits α-amylase and α-glucosidase	[55]
Undaria pinnatifida	Brown macroalga	Fucoidan	Anti-inflammatory, antioxidant, antitumor, anticoagulant, antiviral, and immunomodulatory properties	[56]
Palmaria palmata	Red macroalga	EPA, palmitic acid, oleic acid	Cyclooxygenase 2 (COX-2) inhibition and the relevance to coronary heart disease	[7]
Gracilaria gracilis	Red macroalga	PUFA, omega-3, omega-6	COX-2 inhibition and anti-inflammatory activity	[7]
Ulva lactuca	Green macroalga	Sulfated polysaccharides	Radical scavenging, metal chelating, and cholinesterase inhibitory activities	[7]
Ecklonia cava	Brown macroalga	Fucoidan	Beta-site amyloid precursor protein cleaving enzyme 1 (BACE 1) inhibition with decreased amyloid beta in the Alzheimer's disease context	[7]
Porphyra umbilicalis	Red macroalga	Sulfated polysaccharides, mycosporine-like amino acids (MAAs), phenols	Anti-proliferative, anti-inflammatory, and immunostimulatory activity	[57]
Grateloupia turuturu	Red macroalga	Sulfated polysaccharides	Antioxidant and anti-inflammatory activity	[57]
Kappaphycus alvarezii	Red macroalga	Kappa carrageenan	Forms strong gels used in food applications	[7]

5.1. Carbohydrates and Sulfated Polysaccharides

A distinctive feature of algae is their abundance of complex carbohydrates and dietary fibers, particularly sulfated polysaccharides that are rarely found in terrestrial plants [15,16]. Macroalgae synthesize group-specific polysaccharides: for example, the cell walls of brown seaweeds contain sulfated polysaccharides such as laminarin and alginate as well as fu-

coidan, which is absent in other seaweed groups; red algae produce carrageenans and agar; and green algae produce ulvans, among others [16,58]. These large polysaccharides often function as structural components of algal cell walls or as storage reserves. Although they are not digestible as a source of human energy, they impart significant physiological and health benefits as dietary fibers [58–60]. The polysaccharide content of algae varies considerably by species and can constitute a substantial proportion of dry biomass, highlighting algae as sustainable and renewable sources of structurally diverse bioactive glycans [61]. Algal polysaccharides serve as both soluble and insoluble dietary fibers, supporting digestive health and metabolic regulation [59]. The major polysaccharides derived from algae and their associated biological functions are summarized in Figure 1. Among seaweed fibers, fucoidan, a sulfated fucose-rich polysaccharide abundant in brown seaweeds like *Fucus vesiculosus* and *Undaria pinnatifida*, has attracted extensive research for its broad bioactivity [62,63]. Fucoidan has demonstrated immune-modulating properties and protective effects on gut health [63]. It can act as an anti-inflammatory, antiviral, and antioxidant agent, highlighting its therapeutic potential [63]. Polysaccharides such as carrageenan and agar, extracted from red algae, are widely used in the food industry as gelling, thickening, and stabilizing agents and are also regarded as dietary fibers, as they resist digestion in the human gut but can be partially fermented by colonic bacteria [48,59,64].

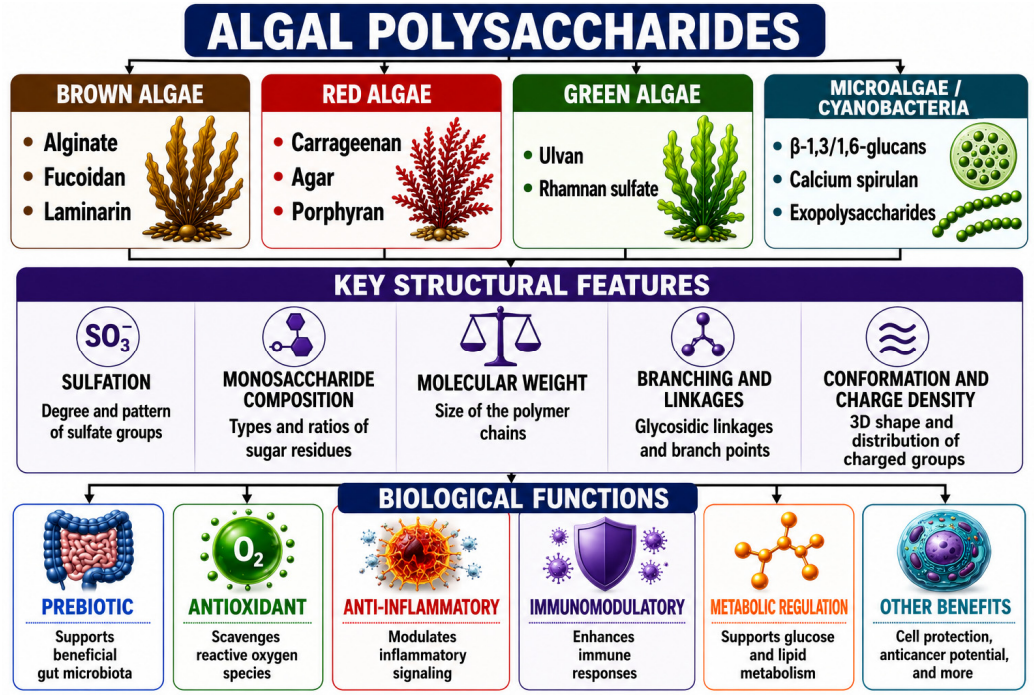


Figure 1. Major polysaccharides derived from brown, red, and green algae, as well as microalgae and cyanobacteria, and their associated biological functions. The figure was created using BioRender and subsequently polished with assistance from ChatGPT (OpenAI) to improve visual clarity, refine layout, and enhance formatting and readability.

Microalgae are also rich in polysaccharides, which can represent a substantial portion of their dry biomass. In some species, polysaccharides may account for 15–75% of total dry weight, whereas in others, polysaccharide synthesis is stimulated by environmental or cellular stress [65]. A unique sulfated polysaccharide, calcium spirulan, is derived from *Arthrospira platensis* and exhibits strong antiviral activity due to the chelation of calcium ions with sulfate groups on the polysaccharide [66]. Additionally, algae are rich in other bioactive fibers, such as β-glucans [67]. Among the various polysaccharides, β-glucans are particularly significant, occurring in algae as either storage carbohydrates or struc-

tural components of the cell wall. These compounds exhibit strong immunomodulatory properties [68]. They exert a potentiating effect on the immune system against microbes and toxic substances by "priming" innate immune cells to respond more effectively to pathogens [68]. They also help reduce serum cholesterol by increasing bile excretion. Overall, algal polysaccharides serve as non-digestible dietary fibers that promote gut microbial balance, modulate the immune system via microbiota-derived metabolites, and simultaneously confer valuable technological properties, such as thickening, gelling, and stabilization in food systems [48,59,61,64].

5.2. Algal Lipids and Polyunsaturated Fatty Acids

Algae are rich reservoirs of structurally diverse bioactive lipids, including a wide range of acyl lipids and fatty acids that differ significantly from those found in terrestrial plants and many marine organisms [69]. In algal cells, fatty acids are primarily incorporated into membrane phospholipids and glycolipids, where they contribute to cellular integrity, metabolic regulation, and stress adaptation [69,70]. Beyond their biological role in growth and survival, algal lipids possess considerable commercial value, serving as alternative sources of saturated, monounsaturated, and PUFAs, including long-chain omega-3 PUFAs such as EPA and DHA, which are widely incorporated into functional food and nutraceutical formulations [69]. Many microalgae can accumulate large amounts of oil under optimized culture conditions, with reported oil productivities per unit area 10–20 times higher than conventional terrestrial oilseed crops [21]. Notably, some marine microalgae, such as *Schizochytrium* (a thraustochytrid alga), accumulate lipids representing 50–70% of dry cell weight, of which DHA constitutes approximately 40–50%, highlighting their suitability for commercial omega-3 production [71]. Other commercially important DHA-producing microalgae include *Ulkenia* sp. and *Crypthecodinium cohnii*, which are cultivated at an industrial scale to produce vegetarian omega-3 oils. These oils are especially valued for their high levels of long-chain omega-3 PUFAs, particularly DHA (22:6 *n*-3) and, in certain strains, EPA (20:5 *n*-3) [71,72]. Omega-3 PUFAs such as EPA and DHA play central roles in neurodevelopment, cardiometabolic health, and the modulation of inflammatory responses. Traditionally, humans have obtained EPA and DHA from fish and seafood [72]. However, these long-chain omega-3 fatty acids are originally biosynthesized by microalgae at the base of the marine food web and subsequently accumulate in higher trophic organisms [73]. Microalgae, therefore, represent a direct and sustainable source of EPA and DHA [72]. Clinical trials have demonstrated that algal oil supplementation effectively increases circulating omega-3 levels in humans, with bioavailability comparable to fish oil [74]. Algal oils offer additional benefits: they are produced in controlled environments (e.g., fermenters or photobioreactors) and are free of contaminants that can accumulate in wild fish, such as mercury, dioxins, and polychlorinated biphenyls, making them a safe source of omega-3s [75].

While microalgae are notable for their high lipid accumulation, most macroalgae (seaweeds) contain relatively low lipid levels, typically only 1–5% of dry weight. Although this is substantially lower than the lipid content of marine fish, seaweeds remain a valuable source of functional lipids due to their vast abundance and large biomass availability in coastal ecosystems [59]. However, within that small lipid fraction, seaweeds do provide beneficial fatty acids. Many brown seaweeds, for instance, contain EPA as a notable portion of their fatty acids, as well as some AA and LA (both omega-6) [76]. Red and green seaweed often have significant levels of ALA (omega-3) and LA (omega-6), albeit in small absolute quantities. In addition to these commonly reported fatty acids, several macroalgal species exhibit distinct lipid profiles; for instance, brown algae such as *Laminaria ochroleuca* and *Undaria pinnatifida* are rich in octadecatetraenoic acid, an omega-3 PUFA, while the green seaweed *Ulva pertusa* contains notable levels of hexadecatetraenoic acid (omega-3)

together with oleic acid (omega-9) and palmitic acid (saturated fatty acid) [76]. Interestingly, seaweed lipids are predominantly polar lipids, particularly glycolipids and phospholipids that constitute cellular membranes, rather than storage triacylglycerols [77]. Some studies suggest that these algal polar membrane lipids may have bioactive properties of their own, such as anti-inflammatory or antiproliferative effects [76,77]. Furthermore, algae provide other lipid-soluble nutrients: certain microalgae and seaweeds are good natural sources of vitamins such as vitamin E (tocopherols) and vitamin K, as well as unique sterols [59]. One of the most prominent algal sterols is fucosterol, which is abundant in brown algae and has been reported to regulate genes involved in cholesterol homeostasis and improve glucose metabolism in experimental studies [78–80].

5.3. Proteins

Algae, including both macroalgae and microalgae, are increasingly recognized as promising sources of dietary protein due to their favorable amino acid composition and nutritional value [81]. The protein content of macroalgae varies considerably among taxonomic groups [22]. Brown seaweeds generally contain relatively low protein levels, typically ranging from about 3–15% of dry weight, whereas red and green seaweeds may contain substantially higher levels, ranging from approximately 10–47% of dry weight [22]. In general, algal proteins contain all essential amino acids required for human nutrition, although the relative abundance of individual amino acids varies among species [82,83]. Several seaweed species exhibit amino acid profiles comparable to those of conventional protein sources [83]. For example, the red alga *Palmaria palmata* contains high levels of essential amino acids, such as leucine, valine, and methionine, with concentrations comparable to those reported for ovalbumen, while isoleucine and threonine levels are comparable to those found in legume proteins [83,84]. Similarly, the green seaweed *Ulva rigida* contains high concentrations of leucine, phenylalanine, and valine, and its histidine content is comparable to that reported for legumes and eggs [82]. In many seaweed species, aspartic acid and glutamic acid are also abundant and contribute to the characteristic umami taste of several algae, including species of *Fucus* and *Ulva* [82,85]. Microalgae are particularly notable for their high protein content. Species such as *Arthrospira* (*Spirulina*) *platensis* and several *Chlorella* species can contain up to 50–70% protein on a dry weight basis, with amino acid profiles comparable to those of traditional dietary protein sources [86].

Another important class of algal proteins is the pigment-protein complexes known as phycobiliproteins. Phycobiliproteins are mainly derived from cyanobacteria and red algae, both of which are rich in proteins [87]. Cyanobacteria such as *Arthrospira platensis* (*Spirulina*) contain about 55–70% protein (dry weight), while red seaweeds contain approximately 2.7–47% depending on the species. In cyanobacteria such as Spirulina, blue phycobiliproteins can account for 8–13% of total dry biomass [88]. In addition to their physiological role in algae, phycobiliproteins have attracted interest for their antioxidant, anti-inflammatory, and hepatoprotective activities and are widely used as fluorescent markers in biotechnology and clinical diagnostics [33,87].

5.4. Pigments

Algal pigments are mainly classified into chlorophylls, carotenoids, and phycobiliproteins, and these pigment groups are responsible for the characteristic green, yellow to orange, and blue to red colors observed across microalgae, macroalgae, and cyanobacteria [86–88]. The major pigments and secondary metabolites derived from marine algae, along with their associated biological relevance, are summarized in Figure 2. Beyond their role in photosynthesis, algal pigments are increasingly valued as bioactive compounds and natural colorants for food, nutraceutical, cosmetic, and pharmaceutical applica-

tions [89,90]. Among these pigments, carotenoids are lipophilic isoprenoid molecules that include carotenes and xanthophylls, with important representatives such as β-carotene, lycopene, zeaxanthin, astaxanthin, lutein, and fucoxanthin, which are frequently reported in algal biomass [33,91]. These carotenoids have attracted considerable interest because they combine color with antioxidant, photoprotective, and anti-aging properties, which support their growing use in value-added formulations [33,89]. β-carotene is an important algal carotenoid because it functions as a provitamin A precursor and contributes orange-yellow pigmentation, whereas astaxanthin and fucoxanthin are recognized for their pigmentation and notable antioxidant and bioactive properties [33,92].

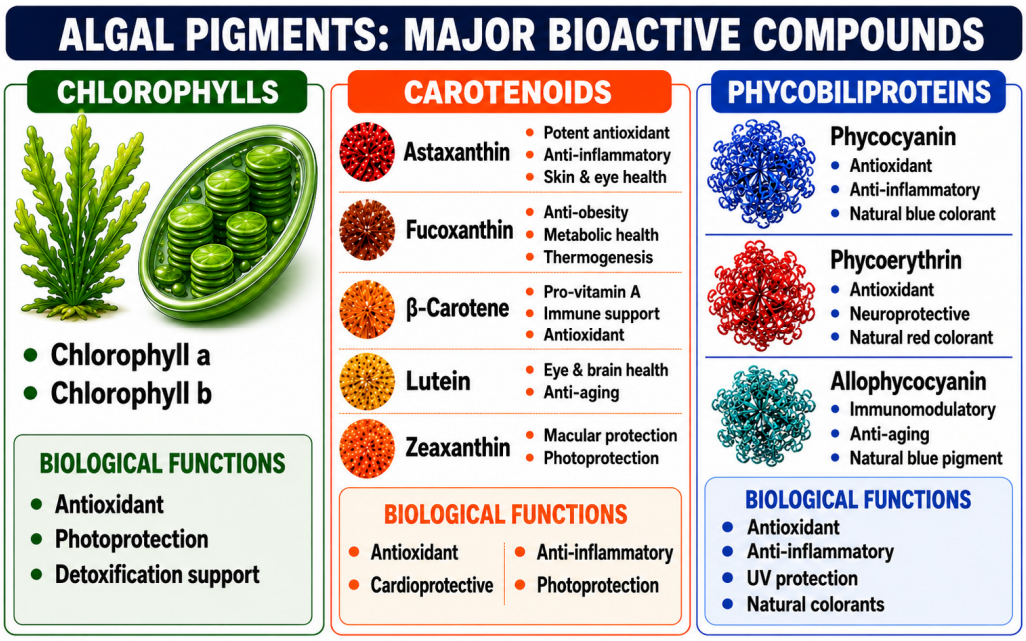


Figure 2. Major pigments derived from marine algae and their associated biological and biotechnological relevance. The figure was created using BioRender and subsequently polished with assistance from ChatGPT (OpenAI) to improve visual clarity, refine layout, and enhance formatting and readability.

Chlorophylls are also important algal pigments, and recent reviews describe them as green photosynthetic molecules that contribute not only to light harvesting but also to the antioxidant value of algal extracts and products [33,93]. Structurally, chlorophylls are magnesium-containing tetrapyrrole pigments, and functionally, they are closely associated with the algal response to ultraviolet (UV)-induced oxidative stress [93,94].

In addition, phycobiliproteins, particularly phycocyanin, phycoerythrin, and allophycocyanin, are attracting growing attention as natural pigments due to their vivid colors, biological activity, and technological value [33,90]. Among them, phycocyanin is particularly important as a natural blue pigment. It has been highlighted for applications in food systems and the cosmetic and pharmaceutical fields due to its antioxidant and anti-inflammatory properties [95]. Krakauskaitė et al. [96] also reported that cosmetic-grade phycocyanin and allophycocyanin can be isolated from *Arthrospira platensis*, supporting their potential incorporation into cosmetic products as functional colorants and bioactive ingredients.

5.5. Phenolic Compounds

Phenolic compounds represent an important class of marine algal secondary metabolites, and recent studies describe them as structurally diverse bioactive compounds associated with antioxidant, anti-inflammatory, antimicrobial, anticancer, antidiabetic, and nutraceutical relevance in seaweed and microalgal systems [1,7,24]. Marine algal phenolics include simple phenols, phenolic acids, flavonoid-like compounds, bromophenols, tannins,

and phlorotannins, although phlorotannins are the most characteristic and extensively studied phenolic group in brown macroalgae [23,24,97]. Brown algae contain phenolic compounds such as bromophenols, tannins, terpenoid-associated phenolics, and phlorotannins, whereas red and green algae generally contain lower or more variable levels of phenolic compounds compared with brown algae [24,97,98].

Phlorotannins are marine polyphenols formed through the polymerization of phloroglucinol units, and they are reported mainly in brown algal families such as Fucaceae, Sargassaceae, and Alariaceae [23,24]. More than 150 phlorotannin structures have been identified from brown seaweeds, and commonly reported structural subclasses include fucols, phlorethols, fucophlorethols, eckols, fuhalols, and carmalols [23,24].

The phenolic profile of marine algae varies with species, taxonomic group, environmental conditions, extraction solvent, and processing method, which makes standardization important for reliable recovery and comparison of algal phenolics across studies [24,57,98]. Peng et al. [98] reported that free and bound phenolic fractions in 11 marine macroalgae from the South China Sea differed in total phenolic content, total phlorotannin content, total flavonoid content, phenolic profile, and antioxidant ability.

Bromophenols are another important group of marine phenolic compounds, and recent studies describe them as halogenated phenolics found in marine algae with antioxidant, metal-chelating, and broader bioactive potential [99–101]. Bromophenols are particularly relevant to marine systems because halogenated aromatic metabolites are more characteristic of marine organisms than terrestrial plants, and their biological behavior depends on phenolic hydroxyl groups, bromination pattern, catechol structures, and linkage type [100,101]. Boulebd [100] reported that natural marine bromophenols can scavenge hydroperoxyl radicals and chelate metals, with antioxidant reactivity influenced by C–O–C or C–C linkages and catechol functionality.

The biological relevance of algal phenolic compounds is closely associated with their hydroxyl-rich structures, which support radical scavenging, metal chelation, modulation of oxidative stress, and interaction with inflammatory and metabolic pathways [23,24,99]. Studies on seaweed-derived phenolics report antioxidant, anti-inflammatory, antimicrobial, antidiabetic, anti-obesity, and anticancer-related activities, although the strength of evidence varies depending on whether the data comes from chemical assays, cell culture, animal studies, or human trials [23,24,99].

6. Mechanisms of Action of Marine Algal Bioactive Compounds

Marine algal bioactives act through compound-specific and structure-dependent mechanisms, and their activity is repeatedly reported to vary with factors such as sulfation pattern, molecular weight, chain length, phenolic polymerization, peptide sequence, and lipid structure [1,23,37]. These mechanisms converge mainly on redox control, inflammatory signaling, target-enzyme inhibition, host–microbe interactions, and, for selected compounds, regulation of apoptosis and cell-cycle progression [1,23,102]. Presenting the evidence at the pathway level clarifies the biological mechanisms through which marine algal compounds exert their effects [1,37]. The major mechanisms through which marine algal bioactive compounds exert biological effects are summarized in Figure 3.

Carotenoids such as astaxanthin and fucoxanthin are primarily described as redox-active and inflammation-modulating molecules rather than simple pigments [102,103]. Astaxanthin is consistently reported to modulate the Nrf2 and NF-κB axes, with effects including activation of antioxidant defense programs and suppression of pro-inflammatory transcriptional signaling [103]. Fucoxanthin is likewise associated with ROS reduction, Nrf2/HO-1 activation, and NF-κB downregulation, and a recent primary study in LPS-treated THP-1 macrophages showed reduced levels of inflammatory mediators, along

with regulation of both Nrf2/HO-1 and NF-κB p65 signaling [104,105]. These pathway-level actions provide the mechanistic basis for the compound-specific formulation and application sections that follow later in the manuscript [103,104].

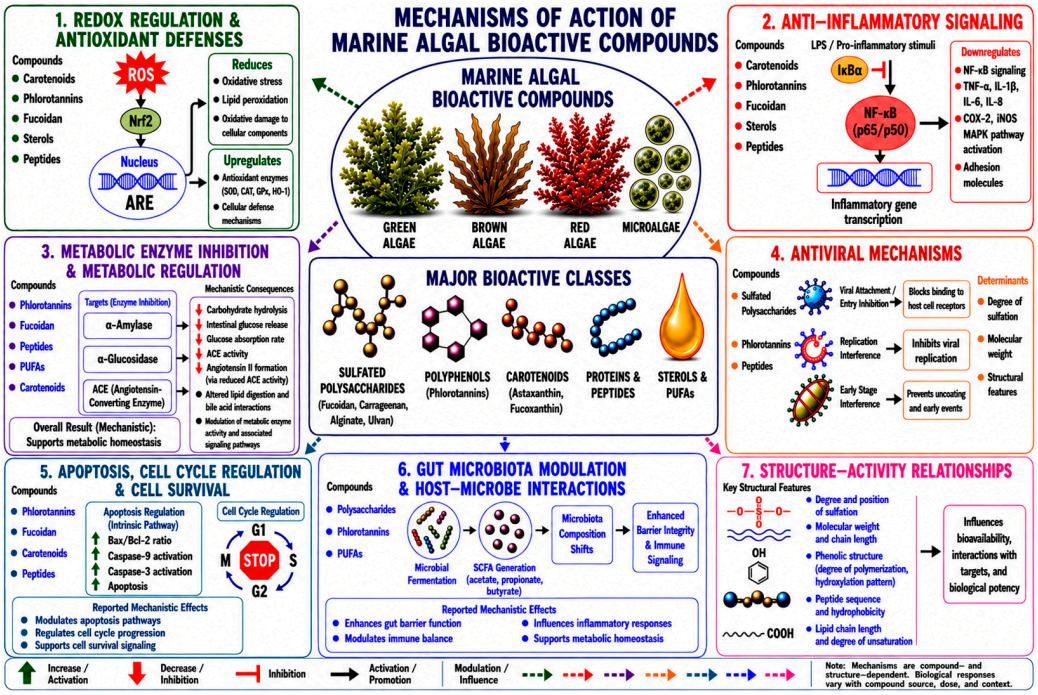


Figure 3. Mechanisms of action of marine algal bioactive compounds, including polysaccharides, polyphenols, carotenoids, peptides, sterols, and polyunsaturated fatty acids (PUFAs). These compounds act through redox regulation involving nuclear factor erythroid 2-related factor 2 (Nrf2), inflammatory signaling modulation involving nuclear factor kappa B (NF-κB), metabolic enzyme inhibition involving α-amylase, α-glucosidase, and angiotensin-I-converting enzyme (ACE), antiviral interference, apoptosis and cell cycle regulation, and gut microbiota modulation, with effects influenced by relationships between compound structure and biological activity. The figure was created using BioRender and subsequently polished with assistance from ChatGPT (OpenAI) to improve visual clarity, refine layout, and enhance formatting and readability.

Among sulfated polysaccharides, fucoidan, carrageenan, and ulvan are repeatedly linked to antioxidant, anti-inflammatory, immunomodulatory, and antiviral mechanisms, with function strongly influenced by sulfation and molecular size [1,106,107]. Fucoidan is a regulator of inflammatory signaling by suppressing NF-κB-associated cytokines and enzymes, while also affecting leukocyte adhesion, enzyme activity, and apoptosis-related pathways in selected models [106,107]. Carrageenans and related marine sulfated polysaccharides are classically described as antiviral agents that interfere with viral attachment, entry, and early replication events, and these effects are reported to depend on structural features such as degree of sulfation and molecular weight [108]. Ulvan is also described as an immunomodulatory sulfated polysaccharide, and recent reports indicate that ulvan-derived forms can suppress LPS-driven inflammation and support epithelial barrier integrity in intestinal models [109,110].

Phlorotannins, the characteristic polyphenols of brown algae, are repeatedly described as multitarget molecules whose hydroxyl-rich structures support ROS scavenging, metal chelation, and interference with inflammatory signaling pathways [23,55]. Studies focused on brown-algal phlorotannins also identify α-amylase and α-glucosidase inhibition as central metabolic mechanisms, which link this class to modulation of postprandial carbohydrate handling rather than to broad disease claims alone [55]. In addition, phlorotannins are reported to modulate MAPK/NF-κB signaling and to participate in apoptosis and

cell-cycle control in experimental tumor-related models, which supports their classification as mechanistically pleiotropic rather than single-target compounds [23,111].

For the protein fraction, the strongest mechanistic evidence currently centers on bioactive peptides that inhibit angiotensin-I-converting enzyme (ACE) and on selected protein-pigment complexes with antioxidant and anti-inflammatory activity [37,112]. A recent review of marine peptides reports that algae-derived peptides interact with the ACE active region through hydrogen bonding, van der Waals interactions, and, in some cases, metal coordination, and examples from *Ulva*, *Porphyra*, *Laminaria*, and *Undaria* show how peptide sequence determines inhibitory potency and binding mode [37]. For proteinaceous pigments, a recent review of C-phycocyanin describes antioxidant and anti-inflammatory effects associated with radical-quenching behavior and downregulation of inflammatory mediators, including NF-κB-linked responses in experimental systems [112,113]. These mechanistic features justify treating algal proteins and peptides as functional ingredients and delivery-relevant bioactives rather than solely as nutrients [37,112].

Marine algal sterols and PUFAs extend this mechanistic range by acting through membrane-associated and lipid-signaling pathways, while polysaccharides and phenolics also contribute indirectly through the gut microbiota [114–116]. The brown-algal sterol fucosterol has been shown to regulate Nrf2/HO-1 and NF-κB/MAPK signaling in inflammatory stress models, supporting a mechanism that couples antioxidant defense with inflammatory suppression [116]. For algal EPA and DHA, recent studies report anti-inflammatory effects through altered membrane composition and reduced synthesis of pro-inflammatory eicosanoids, alongside broader effects on inflammatory tone and resolution pathways [114,117]. Taken together, these mechanisms show that marine algal bioactivity depends not only on intrinsic chemistry but also on structure, matrix, and biotransformation.

7. Extraction, Isolation, and Characterization of Marine Bioactive Compounds

The recovery of marine algal bioactives depends on coordinated workflows that include pretreatment, cell disruption, extraction, purification, and analytical characterization, because algal matrices differ widely in cell wall complexity and target compounds differ substantially in polarity, stability, and abundance [12,38,39]. In marine microalgae, pretreatment is repeatedly described as a critical step because rigid polysaccharide protein cell walls can limit solvent penetration and reduce the release of intracellular compounds [38,39]. Recent reviews identify bead milling, high-speed homogenization, pulsed electric field treatment, ultrasonication, microwave treatment, freeze-thawing, and enzymatic or chemical hydrolysis as major disruption strategies for improving extraction efficiency [38,39]. This need for matrix disruption is not limited to microalgae, as macroalgal extraction is also affected by polysaccharide-rich cell walls and the coexistence of metabolites with different physicochemical properties, making selective, energy-aware extraction design important for algal biorefinery development [12,118]. Although conventional solid–liquid extraction and related solvent-based approaches remain widely used in algal processing, these methods are often limited by long extraction time, low selectivity, and substantial solvent consumption [118,119]. For that reason, recent marine algal studies increasingly prioritize green and intensified extraction methods, including ultrasound-assisted extraction, microwave-assisted extraction, enzyme-assisted extraction, pressurized liquid extraction, supercritical fluid extraction, ionic liquids, and deep eutectic solvents [98–100]. These approaches are relevant because they are intended not only to improve extraction yield but also to preserve compound integrity, reduce hazardous solvent use, and support the development of algae-derived bioactives for food, pharmaceutical, cosmetic, and biotechnological applications [98–100]. Common extraction, processing, and analytical methods used

to recover and characterize algae-derived compounds are summarized in Table 2. Recent studies demonstrate how extraction methods can be selected and optimized for the target compound. For example, Ummat et al. [120] optimized ultrasound-assisted extraction of alginate from the solid byproduct remaining after fucoidan extraction from *Fucus vesiculosus*, and their FTIR and thermal analyses showed that ultrasound-treated alginate displayed characteristics like commercial sodium alginate without negatively affecting alginate properties. Similarly, Zhang et al. [121] optimized enzyme-assisted ultrasonic extraction of polysaccharides from *Schizochytrium limacinum* meal, followed by chromatographic purification and structural analysis, and reported that the purified SLMP1-1 fraction had an α configuration and strong antioxidant activity in 2,2-diphenyl-1-picrylhydrazyl (DPPH), ABTS, and ferric ion reduction assays. These studies show that extraction is not simply a recovery step, but a process that can influence the yield, structural quality, and functional activity of marine algal bioactives.

Table 2. Extraction and purification methods used for algal bioactives.

Method	Algal Source	Target Compounds	Advantages or Outcome	Reference
Conventional solvent extraction	*Arthrospira platensis*	Phycocyanin, allophycocyanin	Maceration provided a favorable balance of yield, purity, and recovery before further purification	[96]
Ultrasound-assisted extraction	*Fucus vesiculosus* seaweed by-product	Alginate	Reduced extraction time and produced alginate with characteristics comparable to conventionally extracted and commercial sodium alginate	[120]
Microwave-assisted extraction	*Ascophyllum nodosum*; *Laminaria hyperborea*	Phenolic compounds	Improved recovery of phenolic compounds under optimized conditions	[118]
Enzyme-assisted extraction	*Schizochytrium limacinum* meal	Polysaccharides	Improved polysaccharide yield: purified fraction showed antioxidant activity in 2,2-diphenyl-1-picrylhydrazyl (DPPH), 2,2′-azinobis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), and ferric ion reduction assays	[121]
Supercritical CO_2 extraction	*Undaria pinnatifida* stem	Fucoxanthin	Effective extraction of fucoxanthin from waste stem biomass under optimized conditions	[122]
Pressurized liquid extraction	*Saccharina latissima*	Fucoidan, laminarin, alginate	Green technique with shorter extraction time and reduced solvent use; different target compounds required different extraction conditions	[123]
Deep eutectic solvent extraction	*Ascophyllum nodosum*; *Laminaria hyperborea*	Phenolic compounds	Green extraction approach with high total phenolic recovery under optimized conditions	[118]
Solid–liquid extraction followed by ultrafiltration	*Gracilaria* sp.	MAAs, phycobiliproteins, non-fluorescent proteins	Enabled separation of distinct bioactive-rich fractions; the MAA-rich fraction showed enhanced antioxidant activity	[124]

Table 2. *Cont.*

Method	Algal Source	Target Compounds	Advantages or Outcome	Reference
Centrifugal partition chromatography after eco-extraction	*Tisochrysis lutea*	Fucoxanthin	Centrifugal partition chromatography enabled one-step separation and purification of fucoxanthin from other pigments	[125]
Pulsed electric field cell disruption	*Arthrospira platensis*	water-soluble proteins, C-phycocyanin, and carbohydrates	Non-thermal electroporation preserves heat-sensitive bioactives; energy demand and scale-up considerations	[126]

Green extraction is also increasingly important for extracting macroalgal phenolics and polysaccharides. Jesus et al. [118] reported that combining deep eutectic solvents with microwave-assisted extraction provided a sustainable route for extracting bioactive compounds from *Ascophyllum nodosum* and *Laminaria hyperborea*, while analytical tools such as high-performance liquid chromatography (HPLC), Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), and thermal analysis were used to confirm phenolic recovery, functional groups, cell wall disruption, and changes in extracted biomass and residues. The importance of target-specific optimization is further demonstrated by brown seaweed polysaccharides, as reported by Khajavi Ahmadi et al. [123], who evaluated the effects of extraction parameters on the recovery of fucoidan, laminarin, and alginate from *Saccharina latissima* using both conventional and advanced extraction methods. These findings support the need for compound-specific extraction design, as different algal bioactives require distinct solvent systems, processing conditions, and recovery strategies. Carotenoid extraction also benefits from targeted green processing approaches. Yin et al. [122] optimized supercritical CO_2 extraction of fucoxanthin from *Undaria pinnatifida* stem byproducts using response surface methodology, highlighting supercritical CO_2 as a solvent minimizing strategy for recovering fucoxanthin from an underused algal side stream. Electrical pretreatment methods provide another route to selective recovery, as Carullo et al. [126] showed that pulsed electric fields increased the extractability of water-soluble proteins, C phycocyanin, and carbohydrates from *Arthrospira platensis*. The same study reported that combining pulsed electric fields with mild heating reduced the energy required for C phycocyanin recovery compared with mild heating alone. Together, these studies show that extraction strategies are increasingly designed to balance compound recovery and process feasibility, both of which are essential for the commercial use of marine algal bioactives.

After extraction, purification becomes essential when the objective shifts from crude bioactive-rich extracts to defined compounds or enriched fractions [121,124,125]. Recent studies demonstrate the use of membrane and chromatographic strategies to separate algal molecules based on size, charge, and partition behavior, rather than relying on extraction alone [121,124,125]. In a multiproduct biorefinery approach using *Gracilaria* sp., Vaz et al. [124] combined solid–liquid extraction with ultrafiltration and induced precipitation to obtain three different fractions, including a final MAA-rich fraction with enhanced antioxidant activity and separate fractions enriched in phycobiliproteins and non-fluorescent proteins. A comparable purification strategy was demonstrated for cyanobacterial MAAs, where Candelo and Llewellyn [127] used sequential membrane filtration to purify and concentrate aqueous MAA extracts while simultaneously separating phycocyanin, resulting in a 3.3-fold increase in the final nanofiltration retentate's shinorine concentration. Chromatographic purification is also important for pigment-rich extracts, as Pajot et al. [125] showed that centrifugal partition chromatography enabled one-step separation of fucoxanthin from

other pigments after eco-extraction from *Tisochrysis lutea*, with final fractions reaching 100% fucoxanthin purity by HPLC.

Analytical characterization is therefore a decisive step in the development of marine algal bioactive compounds because compound recovery must be linked to chemical identity, purity, structure, and functional quality [39,118,120,121]. A recent study on marine microalgae reported that spectrophotometric assays remain useful for rapid screening but are susceptible to interference, whereas advanced chromatographic techniques such as gas chromatography-mass spectrometry (GC-MS), high-performance liquid chromatography-mass spectrometry (HPLC) with diode-array detection, and especially HPLC-MS provide greater specificity and sensitivity for characterizing phenolic compounds in complex algal matrices [39]. Across recent primary studies, HPLC has been used to identify phenolics in deep eutectic solvent microwave extracts of brown algae, FTIR has been used to confirm functional groups in alginate and phenolic rich fractions, SEM has been used to visualize structural disruption after extraction, thermal methods such as thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) have been used to compare extract stability and residue behavior, and proton nuclear magnetic resonance (^{1}H NMR) has been used to support structural confirmation of purified polysaccharides [118,120,121]. These analytical steps are important because the industrial value of marine algal bioactives depends not only on extraction yield, but also on compound identity, structural integrity, reproducibility, and suitability for downstream applications [39,118,120,121].

8. Bioaccessibility, Bioavailability, and Delivery Strategies for Marine Algal Bioactives

The practical use of marine algal bioactives is often limited by low chemical stability, poor oral bioavailability, and formulation-related challenges, which reduce their applicability in the food, nutraceutical, pharmaceutical, and environmental protection sectors [13,128]. Seaweed phenolic compounds, especially phlorotannins, have been reported to have low oral bioaccessibility and bioavailability despite their biological activity, and their absorption can be influenced by the food matrix, processing methods, and gut microbiota composition [25]. For orally consumed bioactive compounds, poor stability and limited bioavailability can reduce functional efficacy when compounds have low aqueous solubility, are sensitive to heat, light, oxygen, and pH, exhibit poor intestinal permeability, or undergo extensive first-pass metabolism [129]. This issue is especially relevant to marine algal bioactives because microalgae synthesize a chemically diverse array of compounds, including PUFAs, carotenoids, phycobiliproteins, peptides, sterols, polysaccharides, phenolic compounds, vitamins, MAAs, and alkaloids, which differ in solubility, stability, digestibility, and absorption behavior [1]. Protein bioavailability is an important consideration because macroalgal proteins can be affected by the complex seaweed cell wall matrix, dietary fiber, polysaccharides, and phenolic compounds, which may reduce protein accessibility during digestion [22]. O'Brien et al. [22] reported that phenolic compounds can bind to proteins and reduce nutrient bioavailability, while polysaccharide-rich seaweed cell walls can make proteins less accessible to gastrointestinal enzymes. Lipid bioavailability is comparatively better supported by human evidence, as Bailey et al. [130] reported that plasma phospholipid DHA and EPA bioavailability from microalgal oil supplements was statistically non-inferior to fish oil in a randomized double-blind placebo-controlled trial involving 74 adults over 6 and 14 weeks. The same study concluded that microalgal oil is a reliable and bioavailable source of DHA and EPA, supporting its relevance for functional food and nutraceutical applications. Carotenoids pose a different delivery challenge because fucoxanthin, a marine algae-derived carotenoid with pharmaceutical and nutraceutical

potential, has a highly unsaturated structure that contributes to instability, poor aqueous solubility, and limited bioavailability [128].

Nanoencapsulation has been shown to improve fucoxanthin delivery, as Koo et al. [131] reported that nanoparticles containing *Phaeodactylum tricornutum* extract achieved fucoxanthin encapsulation efficiencies above 78%, controlled release during simulated gastrointestinal digestion, 1.8-fold improvement in Caco 2/TC7 membrane permeability, and 31.8% to 332.1% higher plasma absorption of fucoxanthin metabolites in mice compared with non-encapsulated extract. Astaxanthin is another relevant algal carotenoid, produced naturally by *Haematococcus pluvialis*; however, its lipophilic nature and low oral bioavailability limit its commercial application in functional foods and cosmetic products [91,132]. In a pharmacokinetic study in healthy male volunteers, Khayyal et al. [132] reported that micellar astaxanthin reached a higher plasma maximum concentration more rapidly than native astaxanthin, demonstrating that the formulation strategy can improve the systemic exposure of algal carotenoids. Recent work on Ulva bioactives further shows that low chemical stability, poor oral bioavailability, and undesirable sensory traits can restrict practical use, while encapsulation by spray drying and freeze drying can help preserve stability, antioxidant activity, and handling properties of *Ulva*-derived powders [13].

Overall, current evidence indicates that the functional performance of marine algal bioactives is governed by compound-specific stability, matrix interactions, and delivery system design, underscoring the need for integrated strategies to enhance bioavailability for effective application.

9. Applications of Marine Algal Bioactive Compounds

Marine algal bioactive compounds are increasingly investigated for downstream applications in food, nutraceutical, pharmaceutical, cosmetic, and biotechnological systems because marine algae provide structurally diverse compounds such as polysaccharides, pigments, lipids, peptides, phenolics, sterols, vitamins, and mycosporine-like amino acids (MAAs) with reported functional and biological relevance [1,7]. In food systems, marine algae are used both as whole biomass ingredients and as extract-derived functional ingredients, with established uses including seaweed-derived hydrocolloids for texture modification and microalgal pigments and oils for natural coloration and nutritional fortification [1,26]. Seaweed-derived polysaccharides such as alginate, agar, and carrageenan are widely used in food applications due to their gelling properties, renewability, and suitability for edible films and coatings that help maintain food quality during storage [26]. Beyond food applications, sulfated polysaccharides from marine algae, including carrageenan, fucoidan, and ulvan, are being investigated in biomedical fields such as hydrogels for wound healing, drug delivery, and tissue engineering due to their bioactivity, gel-forming capacity, and biocompatibility [27]. Cosmetic and cosmeceutical applications are also expanding, as marine algal polysaccharides are described as multifunctional cosmetic ingredients with antioxidant, anti-inflammatory, anti-aging, hydrating, and regenerative properties, while algal carotenoids and MAAs are investigated for skin health and photoprotective uses [133–135]. The downstream applications of marine algae-derived bioactive compounds across major product sectors are summarized in Figure 4.

Collectively, these applications show that the value of marine algal bioactives depends not only on their biological activity, but also on their performance in formulated systems, including their ability to modify texture, improve stability, provide natural color, support delivery, and function as bioactive ingredients in food, pharmaceutical, cosmetic, and biotechnological products [1,7,27].

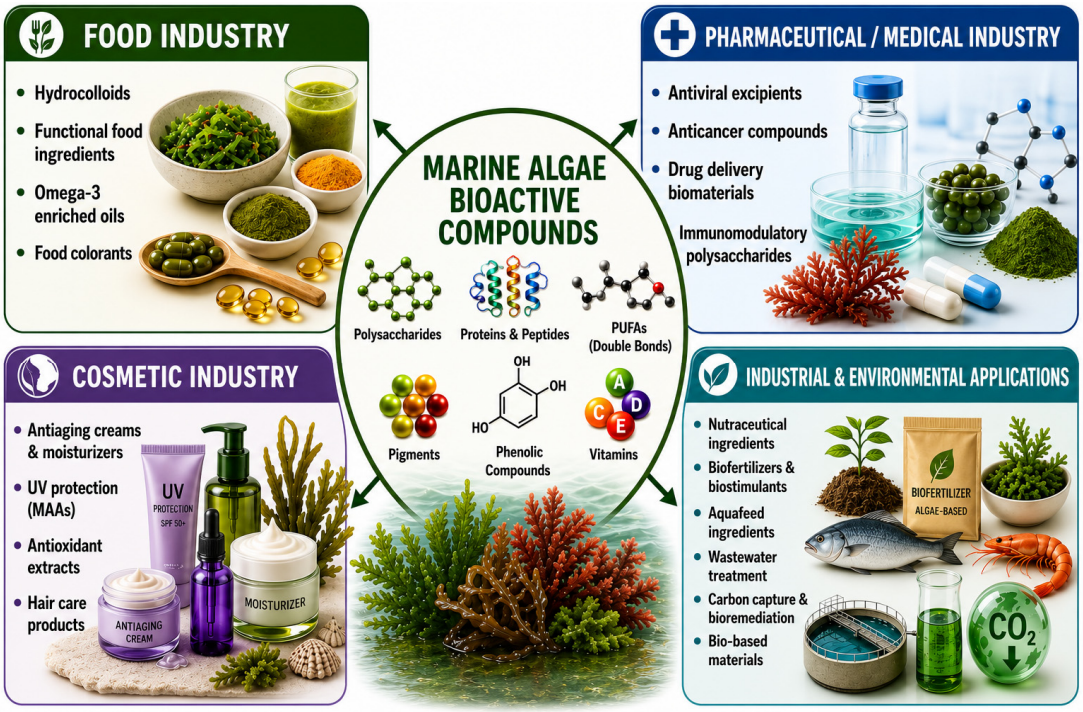


Figure 4. Overview of downstream applications of marine algae-derived bioactive compounds across food, pharmaceutical, cosmetic, agricultural, aquaculture, industrial, and environmental sectors. CO_2 ↓ indicates carbon capture and reduced CO_2 levels. The figure was created using BioRender and subsequently polished with assistance from ChatGPT (OpenAI) to improve visual clarity, refine layout, and enhance formatting and readability.

9.1. Food Applications

Marine algal bioactive compounds are incorporated into food systems as whole-biomass ingredients and as extract-derived functional components that modify texture, color, and nutritional composition [28,136]. Among the most established uses are seaweed-derived hydrocolloids, particularly agar and carrageenan from red algae and alginate from brown algae, which function as gelling, thickening, and stabilizing agents in processed foods [136,137]. Microalgal pigments are gaining importance as natural coloring agents in foods, with phycocyanin-based ingredients reported for use in confectionery products, ice cream, chewing gum, and jellies [33]. Microalgal compounds are increasingly incorporated into formulated foods and nutritional supplements, including beverages, baked goods, and protein products, to enhance nutritional quality and reinforce their role as a functional ingredient in modern food development [48,86,138]. This functional relevance is further supported by the technofunctional properties of algal proteins, which exhibit gel-, film-, foam-, and emulsion-forming abilities that are valuable in food processing systems [83]. The applications of bioactive compounds from marine algae in foods and nutraceutical formulations are summarized in Table 3.

Formulation studies have shown that incorporating Spirulina biomass can improve the nutritional profile of food products while maintaining acceptable sensory and textural properties, reflecting its protein, pigment, and other bioactive compound content [139]. Beyond pigments and hydrocolloids, microalgae are widely recognized as sustainable sources of long-chain omega-3 fatty acids used in foods and dietary supplements, with DHA-rich oils from species such as *Crypthecodinium cohnii* and *Schizochytrium* commonly used in infant formula fortification and other food applications [140].

Table 3. Applications of marine algal bioactive compounds in foods and nutraceutical formulations.

Algal Ingredient/Extract	Product or Supplement Format	Dose or Inclusion Level	Matrix or Population	Components	Purpose	Nutritional or Health Outcome	Sensory or Technological Outcome	Safety or Tolerability Note	References
Spirulina powder	Vegan basil pesto	1% and 2%	Basil pesto	Protein, minerals, polyphenols, flavonoids	Nutritional fortification of pesto	Protein increased by 35% to 40%; iron increased up to threefold; calcium increased up to 25%; antioxidant activity increased	1% spirulina pesto received the highest overall rating (4.56); texture changes were limited mainly to hardness; consumers still rated fortified pesto highly	No safety issues reported in the product study	[141]
Spirulina powder	Semolina pasta	2% to 15%	Pasta	Protein, phenols, flavonoids, iron, calcium, γ-linolenic acid, Docosahexaenoic acid (DHA)	Functional fortification of pasta	Protein increased up to 77.47%; total phenols up to 76.62%; flavonoids up to 162.88%; iron up to 296.99%; calcium up to 57.27%	No detrimental changes to textural and sensory attributes; 12.5% spirulina pasta was rated liked very much; purchase intention was high	No significant nutrient loss after cooking was reported	[139]
Spirulina algae powder	Gluten-free biscuits and snacks	3%, 6%, and 9%	Quinoa flour biscuits and snacks	Protein, fat, ash, minerals, amino acids	Nutritional improvement of gluten-free products	Dose-dependent enhancement in nutritional value was reported	Water absorption increased with spirulina addition; biscuit weight, volume, and specific volume decreased with increasing spirulina level	Concentrations were selected after preliminary optimization for product quality and economic feasibility	[142]
Fucoxanthin-rich microalgal extract	Oral supplement	8.8 mg day^{-1} fucoxanthin for 12 weeks	Older adults with perceptions of cognitive decline	Fucoxanthin	Cognitive support	Improved some aspects of episodic memory, attention, vigilance, perceptual-cognitive function, awakeness after sleep, and insulin response	Not applicable	No difference in adverse events or side effects versus placebo was found	[52]

Table 3. *Cont.*

Algal Ingredient/Extract	Product or Supplement Format	Dose or Inclusion Level	Matrix or Population	Components	Purpose	Nutritional or Health Outcome	Sensory or Technological Outcome	Safety or Tolerability Note	References
Phaeodactylum tricornutum microalgae extract	Daily oral supplementation	Daily intake for 24 weeks	Healthy older adults with age-associated memory impairment	Microalgae extract derived from *P. tricornutum*	Support cognitive function and inflammatory status	Within-group improvements in Stroop overall reaction time and delayed word recall; hs-CRP decreased from 3.9 mg L^{-1} to 2.1 mg L^{-1} compared with placebo	Not applicable	The product was deemed safe and tolerable with no adverse impact on safety, blood tests, or reported side effects	[143]
Euglena gracilis powder	Oral powder supplement	2 g day^{-1} for 8 weeks	Apparently healthy adults	*Euglena* powder rich in paramylon	Immune support	Supplementation enhanced immune function through natural killer cell activity	Not applicable	Study reported supplementation in apparently healthy participants; no major tolerability concerns were highlighted in the abstracted report	[144]
Fucoidan-rich extract	Capsules	125 mg twice daily or 500 mg twice daily for 90 days	Healthy adults	Fucoidan-rich extract	Gut microbiome modulation	Reported prebiotic effects through modulation of microbial diversity, promotion of beneficial taxa, and enhancement of functional pathways	Not applicable	Human safety assessment and adverse event monitoring were part of the trial	[145]

Table 3. *Cont.*

Algal Ingredient/Extract	Product or Supplement Format	Dose or Inclusion Level	Matrix or Population	Components	Purpose	Nutritional or Health Outcome	Sensory or Technological Outcome	Safety or Tolerability Note	References
Microalgal omega-3 oil	Omega-3 supplement	6 and 14 weeks of supplementation	Adult men and women	DHA and EPA	Omega-3 bioavailability	Plasma phospholipid DHA and EPA bioavailability from microalgal oil was statistically non-inferior to fish oil	Not applicable	Microalgal oil was reported as a reliable and bioavailable source of DHA and EPA	[130]
κ-Carrageenan	Gelling/stabilizing system in dairy and related foods	Effective at 0.01% to 0.02% in dairy systems, as summarized in the review	Chocolate milk, flans, puddings, processed cheese, and ice cream mixes	κ-Carrageenan	Stabilization and weak gel formation in food systems	Not framed as a clinical health outcome in the review	Prevents cocoa sedimentation in chocolate milk and serum separation in ice cream mixes; interacts with κ-casein to stabilize suspensions	The review discusses food functionality rather than human tolerability testing	[130]

9.2. Pharmaceutical and Biomedical Applications

Algal-derived polysaccharides and biopolymers are increasingly investigated for pharmaceutical and biomedical applications, including antiviral formulations, wound-care materials, and bioactive compounds with therapeutic potential [27,146]. Carrageenan (a sulfated galactan from red seaweeds) has been documented to have antiviral activity consistent with interference in virus-cell interactions, and it has been formulated into intranasal products studied for respiratory viral infections [147]. A reanalysis of randomized trial data reported that intranasal iota-carrageenan increased recovery rates in virus-positive cases of the common cold, with effects observed against viruses including coronaviruses and influenza A [148]. These findings support the use of carrageenan-based nasal formulations as algal-derived interventions to reduce respiratory viral burden and symptom duration in controlled settings [147,148]. Fucoidan (a sulfated polysaccharide associated with brown seaweeds) is being investigated in wound repair research, including pathways involved in angiogenesis and tissue remodeling [149]. In in vivo and in vitro studies, fucoidan was reported to accelerate wound healing, accompanied by enhanced blood vessel formation and collagen deposition, with mechanistic signaling pathways linked to AKT/nuclear factor erythroid 2-related factor 2/hypoxia-inducible factor 1 alpha (AKT/Nrf2/HIF-1α) pathway [149]. Alginate-based materials are standard components of modern wound care, and widely available dressings are described to support clinically used moist wound-healing approaches [150]. This clinical wound-care context aligns with broader biomedical use of alginate hydrogels as matrices that can be engineered for biomedical applications. Microalgae are also described as production platforms for high-value bioactive compounds used in nutraceutical and biomedical applications, including pigments and lipid-based products [33,140]. In addition, *Chlamydomonas reinhardtii* is widely studied as a model system for recombinant protein expression and has been explored for applications in oral delivery systems [151].

9.3. Cosmetic and Cosmeceutical Applications

Algae-derived compounds are incorporated into cosmetic and cosmeceutical products as both formulation aids (e.g., thickening and film-forming polysaccharides) and bioactive ingredients associated with photoprotection and skin-conditioning functions [92]. Mycosporine-like amino acids (MAAs) are widely described as natural UV-absorbing metabolites produced by algae and cyanobacteria and are considered promising candidates for protecting against UV-induced skin damage due to their UV-absorbing capacity and reported antioxidant and anti-inflammatory activity in experimental systems [152,153]. Brown seaweed extracts rich in polysaccharides, including fucoidan-associated compounds, have also been reported to exhibit anti-photoaging potential, with clinical studies on extracts from *Undaria pinnatifida* and *Fucus vesiculosus* showing improvements in wrinkle depth and protection against UV-related skin damage [153]. Astaxanthin, a carotenoid biosynthesized primarily by microalgae (notably *Haematococcus pluvialis*), has been repeatedly evaluated in human studies for skin-related outcomes [91,133]. Bjørklund et al. [154] reported clinical data suggesting that astaxanthin intake may reduce wrinkles, water loss, and age spots while improving elasticity and moisture, particularly when combined with topical application. In addition to their bioactive roles, seaweed-derived polysaccharides enhance cosmetic formulation performance by serving as texturizers and stabilizers, thereby supporting their use in gelled and film-forming products such as masks and topical formulations [92]. This formulation role is consistent with the broader use of algae-derived compounds in gelled or film-forming cosmetic formats (e.g., mask-type products), as reported in a cosmetics-focused review of seaweed compounds by Lopez-Hortas et al. [92].

9.4. Agricultural, Aquaculture, and Environmental Applications

Marine algal bioactive compounds are increasingly being evaluated in agriculture, aquaculture, and environmental management because macroalgae and microalgae contain amino acids, polysaccharides, proteins, lipids, phytohormone-like compounds, antimicrobial compounds, carotenoids, vitamins, phenolics, nucleotides, and peptides that have been linked to plant growth promotion, stress mitigation, animal nutrition, immune support, and pollutant removal [155–158]. These applications are especially relevant to sustainable production systems because recent studies and reviews describe algae as resources that can connect bioactive compound production with nutrient recovery, wastewater remediation, carbon dioxide biofixation, and biomass valorization [156–159].

In agriculture, seaweed extracts are widely studied as plant biostimulants because their bioactive fractions can stimulate plant growth, improve nutrient uptake, enhance crop quality, and increase tolerance to abiotic and biotic stresses [155,160]. Seaweed extracts can act through phytostimulatory and phytoelicitor effects, with reported improvements in growth and yield parameters across several crop plants [160]. Kumar et al. [155] reported that seaweed contains amino acids, lipids, carbohydrates, proteins, phytohormones, and antimicrobial compounds, and that seaweed-derived products have been used for plant growth promotion, immunity enhancement, and reduction of biotic and abiotic stresses. Microalgae and cyanobacteria are also biofertilizers, biostimulants, and biopesticides because their biomass contains N-fixing enzymes, soluble amino acids, biomineral conjugates, polysaccharides, phytohormones, micronutrients, and signaling molecules that can influence plant growth and soil fertility [156]. Specific crop studies further support the agricultural relevance of algal bioactives under stress conditions. Carmody et al. [161] compared two carbohydrate-rich *Ascophyllum nodosum* extract formulations and reported significant effects on flower development, pollen viability, and fruit production in tomato under both unstressed and long-term moderate heat stress conditions. In the same study, the formulation produced by high-temperature alkaline processing increased fruit number by 86% compared with untreated plants under heat stress, and the enhanced thermotolerance was associated with lower molecular-weight constituents, increased soluble sugar accumulation, and transcription of protective heat shock protein genes in tomato flowers before fertilization. Seaweed extracts can also improve plant responses to drought, salinity, temperature stress, and pathogens through hormone-related activity, nutrient effects, antioxidant regulation, and activation of plant defense mechanisms [155]. Algal bioactives are also relevant to crop protection, as seaweed extracts have been reported to induce plant defense responses and provide antimicrobial compounds that may reduce plant susceptibility to biotic stress [155]. Kumar et al. [155] described laminarin and sulfated fucans from brown seaweeds as water-soluble polysaccharides that can function as inducers of systemic resistance in plants. Microalgal metabolites may improve soil fertility, stimulate plant defense responses against pathogens, and enhance the uptake of phosphorus, potassium, nitrogen, and other soil minerals [156]. Because crop responses vary with algal species, extraction method, formulation, dose, crop type, and environmental conditions, agricultural translation requires field validation, standardized formulations, dose optimization, and mechanistic studies that link specific algal compounds to plant signaling pathways [155,156,160].

In aquaculture, microalgal bioactives are relevant because microalgae provide EPA, DHA, proteins, vitamins, pigments, phenolic compounds, polysaccharides, nucleotides, and peptides that have been associated with antioxidant, anti-inflammatory, immunostimulant, antifungal, antibacterial, antiviral, and antitumor properties in finfish nutrition research [157]. Tierney et al. [157] reported that marine microalgae provide marine-derived fatty acids and bioactive compounds not commonly found in terrestrial feed ingredients,

with potential benefits for farmed fish health and consumer nutrition. Microalgae are also functional aquafeed ingredients because microalgal proteins, PUFAs, bioactive compounds, and pigments can support aquatic animal growth, immunity, and product quality [162]. The protein content and PUFA abundance of microalgae make them promising alternatives to fishmeal and fish oil in aquafeed formulations [163]. Primary feeding studies provide evidence that selected microalgal ingredients can replace conventional aquafeed inputs without compromising performance in specific fish models [164,165]. Riche et al. [164] conducted a 12-week growth trial in juvenile Florida pompano using fishmeal and fish oil-free diets in which Spirulina and poultry by-product meal served as principal protein sources and *Schizochytrium* algal oil served as the LC PUFA source. That same study also reported that feed intake and survival did not differ between experimental diets and fishmeal control. It concluded that complete co-replacement of fishmeal and fish oil was achieved in Florida pompano by supplying a fishmeal and fish oil-free diet. Sarker et al. [165] tested *Nannochloropsis* sp. QH25 co-product biomass as a fishmeal replacement in rainbow trout diets and reported that 100% replacement produced growth, feed conversion, survival, and fillet composition like the fishmeal reference diet. The same study also reported that rainbow trout fed the 100% replacement diet had the lowest feed cost per kg of fish produced, indicating that microalgal co-products may support both nutritional and economic goals in aquafeed formulation. Microalgae also support the sustainability of aquaculture beyond direct feed replacement, as they have been linked to nutrient cycling, bioremediation, and carbon dioxide biofixation [157]. Microalgae in circular aquaculture systems reduce nutrient discharge, carbon footprint, and operational cost [162]. Tierney et al. [157] stated that microalgae cultivation can avoid resource competition while supporting regenerative farming through bioremediation, nutrient cycling, and carbon dioxide biofixation.

In environmental applications, algae have been reported as agents for wastewater remediation because algal cultures can remove nutrients and pollutants through biosorption, bioaccumulation, intracellular degradation, and biomass production [158]. Algal biomass produced during wastewater remediation can be fractionated into value-added products, including biofuels, food additives, pharmaceuticals, and biofertilizers [158]. Li et al. [159] stated that microalgae can remove or reduce nutrients, organic pollutants, heavy metals, chemical oxygen demand, and biological oxygen demand while producing biomass for biofuels, cosmetics, pharmaceuticals, and nutraceuticals. Wastewater pretreatment, strain performance, suitable treatment infrastructure, and restrictions on downstream biomass use remain major barriers to practical deployment [159]. For heavy metal remediation, living and nonliving microalgal cells are accessible, low-cost, effective, and environmentally friendly materials for removing heavy metals from industrial wastewater [166]. Heavy metal removal by microalgae occurs through mechanisms including biosorption and bioaccumulation, with metal binding mediated by coordination between metal ions and functional groups on the algal cell surface [166]. Morillas-España et al. [167] showed in pilot-scale thin-layer reactors that microalgae-based wastewater treatment removed contaminants of emerging concern more effectively in summer than in winter and, on average, retained less than 3% of pharmaceuticals in the biomass. The same study also reported that the biomass produced demonstrated biostimulant activity in bioassays, supporting a wastewater-to-agriculture pathway once contaminant safety is verified. Seaweed cultivation has also been evaluated as an environmental strategy because it can contribute to climate change mitigation through several pathways. However, not all pathways can be readily integrated into carbon accounting frameworks, and current farming emissions may offset carbon dioxide removal under some scenarios [168]. Most of the carbon fixed by farmed seaweeds currently enters short-term reservoirs, and improving carbon dioxide removal would require decarbonized supply chains, long-term carbon

storage pathways, expanded farming areas, and robust models to track the fate of seaweed carbon [168]. Therefore, environmental claims for algal bioactive production should be framed around measured nutrient recovery, pollutant removal, biomass valorization, and life cycle performance rather than broad sustainability assumptions [158,159,168].

10. Safety, Regulation, and Market Adoption

Although foods and supplements derived from marine algae and their bioactive compounds are increasingly recognized as nutrient-dense ingredients, their wider adoption remains constrained by regulatory, technological, and consumer-related barriers, particularly in Western markets [29]. A central safety issue is that edible seaweeds can contribute to dietary exposure to iodine, cadmium, lead, mercury, total arsenic, and inorganic arsenic, and the European Food Safety Authority specifically evaluated seaweed consumption as relevant to these exposures in the European population [169]. Species and processing method strongly influence the safety profile of seaweed products, as contaminant levels vary across edible seaweeds, and thermal treatment can reduce contaminant concentration and bioaccessibility in some cases [170]. Iodine deserves particular attention because brown seaweeds are widely consumed as natural sources of iodine, yet consumption of high-iodine seaweed species may increase the risk of excessive iodine intake and thyroid dysfunction, particularly in susceptible individuals [171,172]. This concern is supported by a recent clinical study by Aakre et al. [171], which showed that habitual seaweed consumers had iodine intakes above the tolerable upper intake level before seaweed cessation, along with measurable changes in thyroid-related biomarkers after intake was reduced. Recent case evidence likewise confirms that chronic overconsumption of seaweed can lead to hypothyroidism, reinforcing the need for moderation guidance and better consumer awareness around iodine-rich species [173].

Safety oversight is also critical for microalgae-based supplements, particularly cyanobacterial products such as Spirulina, where contamination can occur during production and handling [174]. A retail study reported that spirulina-containing products may contain microcystins at levels approaching recommended intake limits and potentially pathogenic bacteria [174]. Additional market surveillance has confirmed that commercial Spirulina and Chlorella products may contain both beneficial nutrients and undesirable contaminants, emphasizing the need for rigorous quality control [175]. The United States Food and Drug Administration (FDA) guidance similarly states that blue-green algae products can be contaminated with microcystins if companies do not test for these toxins, and it links safe commercialization to good manufacturing practices and contaminant control [176]. Beyond chemical contaminant monitoring, algae-derived ingredients require product-specific toxicological and sensitization assessment because safety can differ between whole biomass, crude extracts, purified metabolites, pigments, proteins, and topical formulations. EFSA-oriented evaluations of microalgae-derived novel foods emphasize strain-level taxonomic identification, manufacturing-process description, compositional and microbiological characterization, toxicological evidence, allergenicity assessment, and intake-based exposure evaluation [30]. Cyanobacterial dietary supplements also require toxin screening because commercial blue-green algal products have been reported to contain microcystins and to show cytotoxicity, supporting routine cyanotoxin testing and dose-based risk assessment [177]. Sensitization should be considered particularly for protein-rich algal products, as a recent review of *Arthrospira*/*Spirulina* allergy reported rare but documented allergic reactions, including anaphylaxis, indicating that allergenicity cannot be excluded solely because the ingredient is naturally derived [178]. For macroalgae, safety evaluation should also include iodine quantification and monitoring of potentially toxic elements, such as arsenic, cadmium, lead, and mercury, because mineral and contaminant levels vary by species,

geography, and source environment [179]. Therefore, safety assessment of marine algal bioactives should integrate taxonomic verification, contaminant and cyanotoxin screening, microbiological quality control, exposure estimation, toxicological testing, allergenicity assessment, and, for topical products, irritation and sensitization testing [30,177–179]. The regulatory landscape for nutraceuticals remains uneven across jurisdictions, with significant differences in safety protocols, product classification, and market entry pathways between the United States, India, Europe, and other regions [180]. In the United States, the FDA states that manufacturers and distributors are responsible for ensuring that dietary supplements are not adulterated or misbranded before marketing, while the FDA mainly exercises post-market enforcement authority [181]. Although algae are still relatively new in the United States food market, several algal species have already been granted FDA "Generally Recognized as Safe" status, indicating that they are considered safe for human consumption [48]. Within the European Union (EU), market access for algae foods has recently improved, as more than 20 algae species were added to the EU Novel Food Status Catalog in 2024, allowing them to be sold as foods or food supplements without separate pre-market authorization when prior traditional use is established [182]. The European Commission explicitly described this update as a reduction of a major bottleneck for the algae sector, as it saves time and costs while maintaining compliance with general EU food safety rules. Even when regulatory access improves, market adoption depends heavily on consumer acceptance, as sensory attributes such as color, flavor, odor, and texture remain key barriers to the adoption of algae-based foods [29].

Studies show that consumers generally accept microalgae at low inclusion levels, but acceptance decreases with strong marine flavor, off-flavors, or changes in appearance [183,184].

Taken together, current evidence indicates that the successful commercialization of marine algal bioactive compounds and algae-derived products depends on effective contaminant control, harmonized regulatory frameworks, robust manufacturing quality assurance, and improved sensory optimization to enhance consumer acceptance [134,142–147].

11. Health Benefits of Algae Bioactive Compounds

Algae are increasingly recognized as health-promoting foods because, beyond their nutritional value, they provide diverse bioactive compounds, including polysaccharides, peptides, PUFAs, pigments, phenolics, and sterols, which have been linked to multiple biological activities [7,10,48]. Recent reviews indicate that these algal bioactives exhibit antioxidant, anti-inflammatory, antidiabetic, cardiometabolic, antimicrobial, immunomodulatory, and anticancer effects, supporting the growing interest in algae as nutraceutical and functional food ingredients [7,10,48]. Current evidence further suggests that the health effects of algae are mediated through several mechanisms, including modulation of oxidative stress and inflammatory pathways, regulation of glucose and lipid metabolism, inhibition of key metabolic enzymes, and interactions with the gut microbiota [34,48]. At the same time, the recent literature consistently notes that the strength of evidence varies across outcomes, with many reported benefits still supported mainly by in vitro and animal studies rather than large, well-standardized human trials [10,48]. For this reason, the health benefits of algae are best interpreted by considering both the specific bioactive compounds involved and the level of evidence available for each disease area or physiological outcome. For example, Phycobiliproteins have attracted interest for their antioxidant, anti-inflammatory, and hepatoprotective activities and are widely used as fluorescent markers in biotechnology and clinical diagnostics [33,87]. Likewise, bioactive peptides derived from algal proteins have been reported to exhibit antihypertensive, antioxidant, antimicrobial, immunomodulatory, anticancer, and antithrombotic activities, although current evidence is largely based on in vitro and experimental models rather than well-established clinical

data [22,86]. These peptides are typically generated through enzymatic hydrolysis, microbial fermentation, or gastrointestinal digestion and are increasingly being explored for their potential in functional foods and therapeutic applications [185].

This context provides a basis for examining the major reported health benefit categories of algae, including antidiabetic effects, anti-obesity and metabolic health support, gut health promotion, cardiovascular protection, immune modulation, neuroprotection, and anticancer potential [10,48].

11.1. Antimicrobial and Antiviral Effects

Antimicrobial and antiviral activities are among the most frequently reported health-related functions of marine algal bioactives. Antimicrobial activity from algae has been reported in microalgae, cyanobacteria, and macroalgae, with active compounds including sulfated polysaccharides, fatty acids, phenolic compounds, phlorotannins, peptides, pigments, and crude extracts [7,186,187]. Algal bioactive compounds are active against Gram-positive bacteria, Gram-negative bacteria, foodborne pathogens, pathogenic fungi, and biofilm-forming microorganisms, although antimicrobial potency varies with algal species, strain, cultivation conditions, extraction solvent, compound purity, and assay method [188–190]. The health relevance of these compounds is closely linked to antimicrobial resistance and biofilm-associated infections, as microbial biofilms increase tolerance to antimicrobial treatments, and marine algae-derived metabolites have been reported to inhibit cell attachment, reduce microbial growth, interfere with quorum-sensing pathways, and disrupt extracellular polymeric substances [189].

Among algal phenolic compounds, phlorotannins are especially important because they are characteristic metabolites of brown algae and have been associated with antibacterial, antifungal, antibiofilm, and anti-fouling activities [84,189,191]. Lemesheva et al. [192] evaluated phlorotannin-rich extracts from 10 brown algal species and reported antibacterial, antifungal, and algicidal activity, with some extracts showing minimum inhibitory concentrations comparable to those of widely used antibiotics. Phlorotannins are structurally diverse oligomers and polymers of phloroglucinol, and their antimicrobial activity has been linked to differences in molecular size, degree of polymerization, structural class, algal source, environmental conditions, and extraction approach [84,189,191].

Microalgal fatty acids and PUFAs also contribute to antimicrobial activity, with reported effects against foodborne and clinical pathogens, including *Escherichia coli*, *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Salmonella* spp., and *Bacillus* spp. [188]. Microalgal fatty acids have been described as membrane-active compounds because they can insert into bacterial membranes, increase permeability, promote pore formation, cause cell lysis, disrupt nutrient transport, and interfere with respiration-linked energy generation [188]. EPA, DHA, γ-linolenic acid, α-linolenic acid, oleic acid, and arachidonic acid (AA) are among the microalgal fatty acids reported to exhibit antimicrobial activity, and their effects have been associated with membrane destabilization and disruption of bacterial metabolic functions [188].

Algal proteins and peptides are another antimicrobial group, as peptide-rich hydrolysates and isolated peptides from microalgae have been reported to inhibit pathogenic bacteria by disrupting membranes, interfering with cell walls, and inhibiting essential intracellular targets [188]. Singh et al. [188] reported that peptides from *Chlorella vulgaris*, *Chlorella sorokiniana*, and *Tetraselmis suecica* have been associated with activity against pathogens such as *E. coli*, *S. aureus*, *Salmonella typhimurium*, *Bacillus cereus*, *P. aeruginosa*, methicillin-resistant *S. aureus* (MRSA), *Listeria monocytogenes*, and *Micrococcus luteus*. These findings support classifying algal proteins and peptides as health-relevant bioactives rather than solely as nutritional components.

Sulfated polysaccharides from marine algae also exhibit broad antimicrobial activity, particularly through antiviral and antibiofilm effects [108,189,193]. Algae-derived polysaccharides, such as carrageenan, alginate, fucans, laminaran, and naviculan, have been reported to inhibit viral binding or internalization into host cells and to suppress viral replication-related processes, such as DNA replication and protein synthesis [108,193]. Marine algal antibiofilm compounds, including fucoidan, phlorotannins, carotenoids, fatty acids, and lipid-derived compounds, have been reviewed as agents that can reduce microbial attachment, disrupt extracellular polymeric substances, and interfere with quorum-sensing pathways [189].

Recent studies support the antimicrobial potential of algal extracts, although activity depends strongly on the solvent system and algal species [194]. Kumaravelu et al. [194] evaluated extracts from *Turbinaria ornata*, *Ulva lactuca*, and *Gracilaria crassa* and reported that the ethyl acetate extract of *U. lactuca* showed the highest antibacterial activity against *Salmonella enterica*, *S. aureus*, and *P. aeruginosa*. The same study linked the biological activity of *U. lactuca* extracts to the presence of phytochemicals and functional groups detected through phytochemical analysis, FTIR, and HPLC profiling.

Despite these findings, antimicrobial claims for algal bioactives should be interpreted carefully because many studies rely on crude extracts, different extraction solvents, different bacterial strains, and assay systems that are not always directly comparable [188,190]. Rapp et al. [190] reported that no microalgae-derived antimicrobials have reached commercialization, despite numerous studies demonstrating antimicrobial activity in microalgal extracts. The same study also emphasized that future antimicrobial development requires standardized extract preparation, antimicrobial testing, reporting frameworks, strain selection, optimized growth conditions, harvesting, cell disruption, and extraction protocols. Therefore, algal bioactives show strong antimicrobial potential, but their translation into health, food safety, pharmaceutical, and biotechnological products requires better compound identification, standardized testing, toxicity assessment, formulation stability, and validation in relevant biological or product systems [186,188,190].

Antiviral activity is most strongly supported for marine algal sulfated polysaccharides from red, brown, and green algae, particularly carrageenan, fucoidan, ulvan, and related anionic polysaccharides [66,195,196]. Recent reviews report that these compounds show activity against several clinically relevant viruses, including influenza virus, human immunodeficiency virus (HIV), herpes simplex virus (HSV), dengue virus, hepatitis B virus, respiratory syncytial virus, and coronaviruses [66,195,197]. The main antiviral mechanisms reported for algal sulfated polysaccharides include direct viral inactivation, inhibition of viral adsorption, interference with viral entry, disruption of viral transcription and replication, and stimulation of host antiviral immunity [66,195,196]. These mechanisms are particularly relevant for enveloped viruses, as many require electrostatic interactions between viral surface proteins and host cell receptors or co-receptors during early attachment and entry. Current evidence also indicates that antiviral effects are structure-dependent rather than universal across all algal polysaccharides, as different carrageenan types, fucoidan fractions, ulvan preparations, and extraction conditions can yield distinct antiviral outcomes [66,195,196].

Carrageenan from red algae is among the best-supported algal antiviral compounds, as iota-carrageenan nasal formulations have been tested in randomized clinical studies for viral upper respiratory infections [198–201]. Eccles et al. [198] reported that an iota-carrageenan nasal spray reduced common cold symptom scores and viral load in adults with early common cold symptoms. Ludwig et al. [199] reported that a nasal spray containing carrageenan reduced the duration of common colds and the viral load in nasal secretions in adult patients. Koenighofer et al. [200] reported that carrageenan nasal spray

reduced disease duration, reduced relapse frequency, and increased viral clearance in virus-confirmed cases of common cold. Ludwig et al. [199] reported that the ICICC phase IV trial did not meet the primary symptom score endpoint over days 2 to 4, although exploratory analyses showed symptom reductions and viral load trends in favor of iota-carrageenan.

SARS-CoV-2 studies further support the preclinical antiviral potential of marine sulfated polysaccharides, although these studies should be interpreted primarily as in vitro evidence [202–204]. Kwon et al. [202] reported that sulfated polysaccharides, including fucoidan-related compounds from *Saccharina japonica*, bound the SARS-CoV-2 spike protein and inhibited SARS-CoV-2 infection in vitro, with the high-molecular-weight fucoidan-related compound RPI-27 showing strong antiviral activity in Vero cells. Song et al. [204] reported that fucoidan from brown algae and iota-carrageenan from red algae showed inhibitory activity against SARS-CoV-2 within the tested concentration range, and pseudovirus assays indicated that spike glycoprotein binding contributed to entry inhibition. Morokutti-Kurz et al. [203] reported that iota-carrageenan neutralized SARS-CoV-2 spike-pseudotyped lentiviral particles and inhibited the replication of wild-type SARS-CoV-2 in vitro. Figueroa et al. [201] reported that iota-carrageenan nasal spray reduced PCR-confirmed COVID-19 incidence compared with placebo in a pilot, randomized, double-blind study among hospital personnel, but the authors described the study as a pilot and noted that larger confirmatory studies are still needed.

Fucoidan from brown algae is another major antiviral algal bioactive, as recent studies describe it as a sulfated, fucose-rich polysaccharide that can inhibit viral attachment, entry, and replication in several viral models [66,195,205]. Pradhan et al. [191] reviewed fucoidan as an antiviral agent and reported that its antiviral activity has been associated with inhibition of viral attachment and replication, as well as stimulation of host immune responses against viral infection. Dong et al. [195] also identified fucoidan as one of the major sulfated polysaccharides derived from edible marine algae with antiviral activity, while emphasizing that antiviral performance depends on structural features and virus type. These findings support fucoidan as a promising antiviral candidate, but the current evidence remains more advanced at the preclinical and mechanistic level than at the human clinical level [191,195].

Green algae-derived ulvan and related sulfated polysaccharides also contribute to the antiviral profile of marine algae, although the evidence base is less clinically developed than that for carrageenan nasal formulations [195,196]. Dong et al. [195] reported that sulfated polysaccharides from green algae, including those from *Ulva* species, exhibit antiviral activity and can act by interfering with viral attachment or at various stages of the viral life cycle. Panggabean et al. [196] similarly reviewed algal sulfated polysaccharides from red, brown, and green algae and found that their antiviral activities depend on structural composition, sulfate content, and viral target.

Algal antiviral bioactivity is not limited to polysaccharides, as proteinaceous compounds, such as lectins, have also been reported as viral entry inhibitors [1,206]. Griffithsin, a lectin originally isolated from the red alga *Griffithsia* sp., has been described as a highly potent, broad-spectrum antiviral protein that binds high-mannose glycans on viral envelope glycoproteins and blocks viral entry [206]. Lee [206] reviewed Griffithsin's activity against clinically relevant enveloped viruses and reported that its antiviral profile is linked to carbohydrate-binding interactions with viral glycoproteins.

Overall, the antimicrobial and antiviral evidence indicates that marine algal bioactives act through multiple mechanisms, including membrane disruption, antibiofilm activity, inhibition of microbial communication, blockade of viral attachment and entry, suppression of viral replication, and modulation of host immune responses; however, translation

into practical products requires standardized extraction, compound-level characterization, toxicity testing, formulation stability, and clinical or application-specific validation.

11.2. Metabolic and Cardiovascular Health

Marine algal bioactives are increasingly studied for their effects on metabolic and cardiovascular health because glucose dysregulation, obesity, dyslipidemia, hypertension, oxidative stress, chronic low-grade inflammation, and cardiovascular disease are physiologically interconnected. Rather than acting through a single pathway, algal compounds such as phlorotannins, sulfated polysaccharides, carotenoids, sterols, peptides, proteins, and omega-3 long-chain PUFAs appear to influence metabolic health through complementary mechanisms involving digestive enzyme inhibition, glucose handling, lipid metabolism, adipocyte function, vascular regulation, inflammatory signaling, and antioxidant defense [207–211]. A major mechanism proposed for these effects is the inhibition of carbohydrate-digesting enzymes, especially α-amylase and α-glucosidase, thereby delaying carbohydrate breakdown and reducing postprandial glucose excursions [209]. Recent reviews describe phlorotannins from brown seaweed as potent inhibitors of both α-amylase and α-glucosidase, highlighting these compounds as promising interventions to reduce postprandial hyperglycemia and improve glucose homeostasis [207,208]. In addition to inhibiting digestive enzymes, recent evidence suggests that seaweed-derived compounds may influence insulin signaling, oxidative stress pathways, and glucose uptake, thereby providing broader metabolic benefits beyond acute glucose control [207,209]. Fucoidan is one of the most studied algal polysaccharides in this context, and a recent study by Din et al. [212] reported that fucoidan extracted from *Sargassum binderi* significantly increased glucose uptake and reduced lipid accumulation in 3T3-L1 adipocytes, supporting its potential relevance to diabetes-related metabolic regulation. Fucoxanthin has also received considerable attention, and a study by Kumarasinghe & Gunathilaka [213] concluded that it is a promising marine carotenoid with preventive and therapeutic relevance for diabetes and related metabolic disorders. Experimental studies further show that seaweed-derived molecules can combine antioxidant activity with inhibition of diabetes-related enzymes, which is important because oxidative stress contributes to β-cell dysfunction and the progression of diabetic complications [207,214]. Human evidence is more limited than preclinical literature, but a systematic review and meta-analysis of brown seaweed interventions by Vaughan et al. [215] reported significant effects on both fasting and postprandial plasma glucose and emphasized that more high-quality randomized trials are still needed.

Obesity is a multifactorial metabolic disorder characterized by excessive accumulation of adipose tissue and is strongly associated with complications such as cardiovascular disease, diabetes mellitus, cancer, and accelerated aging [216]. Algae are often investigated for anti-obesity and metabolic health applications because they provide bioactive compounds, such as polysaccharides, proteins, polyphenols, carotenoids, and omega-3 long-chain PUFAs, which have been associated with beneficial effects on adiposity and lipid absorption and metabolism [217]. Anti-obesity potential of seaweed is linked to several mechanisms, including inhibition of lipid absorption and metabolism, promotion of satiety, and suppression of adipocyte differentiation [217]. Among algal metabolites, fucoxanthin has received particular attention, and recent reviews continue to identify it as a promising marine carotenoid for obesity and related metabolic disorders [64,216,217]. *Cylindrotheca closterium* and *Phaeodactylum tricornutum* are two microalgae species that produce fucoxanthin, which has potential as an anticancer, antioxidant, anti-obesity, anti-diabetic, and anti-inflammatory agent [216]. Brown seaweed constituents, including fucoidans, alginate, laminarin, phlorotannins, carotenoids, and phytosterols, are widely discussed for their

potential to modulate obesity-associated metabolic disturbances, including dyslipidemia, inflammation, hyperglycemia, and insulin resistance [209,217]. Polysaccharides derived from *Enteromorpha clathrata* have been reported to reduce body weight and lower serum triglyceride and cholesterol levels in high-fat-diet-fed mice, effects associated with modulation of the gut microbiota, including an increased abundance of the butyrate-producing bacterium *Eubacterium xylanophilum* [61]. A recent systematic review and meta-analysis of randomized controlled trials by Łagowska et al. [217] concluded that edible seaweed supplementation shows potential for managing obesity and lipid disorders, with significant effects observed when refined or extracted brown seaweed preparations were administered for at least 8 weeks. That same study reported significant reductions in body mass index, fat mass, total cholesterol, and LDL cholesterol. However, the review noted that effects on glucose metabolism were inconsistent or not consistently observed across the included trials. Microalgal products may also contribute to metabolic health support, and a systematic review by Firdaus & Priambodo [218] reported that spirulina supplementation in humans has positive effects on metabolic syndrome, including obesity, hypertension, hyperglycemia, and hyperlipidemia, although the authors noted that dosage, treatment duration, and formulation still require further study. Another study by Fu et al. [219] found that spirulina supplementation in overweight and obese adults improved body weight, lipid profile, and diastolic blood pressure, but had limited effects on body composition and glycemic control. A study by Bai et al. [220] reported that dietary *Sargassum fusiforme* alleviated high-fat diet-induced metabolic abnormalities, supporting its development as a functional food ingredient for metabolic health applications.

Cardiovascular disease refers to a group of disorders affecting the heart, blood vessels, and circulatory system, and it remains one of the leading causes of illness and death worldwide [64]. Marine algae are increasingly being investigated for cardiovascular relevance because they contain peptides, polysaccharides, polyphenols, carotenoids, sterols, omega-3 fatty acids, potassium, and other bioactive compounds associated with major cardiovascular risk factors, including hypertension, dyslipidemia, oxidative stress, and vascular inflammation [209,221,222]. A systematic review and meta-analysis of randomized controlled trials by Arzhang et al. [223] reported that algae supplementation significantly reduced triglycerides, total cholesterol, low-density lipoprotein (LDL) cholesterol, and diastolic blood pressure in adults. Another study by Casas-Agustench et al. [222] reported that edible algae intake significantly lowered both systolic and diastolic blood pressure, with stronger effects observed for whole algae intake, doses above 3 g day^{-1}, and interventions lasting at least 12 weeks. One mechanism proposed for these antihypertensive effects is the activity of seaweed-derived bioactive peptides, which can inhibit angiotensin-converting enzyme (ACE), thereby reducing the formation of the vasoconstrictor angiotensin II [222]. *Undaria pinnatifida* is identified among the seaweeds reported to yield ACE-inhibitory peptides with relevance to blood pressure control [222]. In addition to *Undaria pinnatifida*, seaweeds such as *Gracilariopsis lemaneiformis*, *Porphyra yezoensis*, and *Pyropia yezoensis* have also been reported as sources of peptides with possible antihypertensive activity [48]. Peptides obtained from Spirulina proteins, such as Ile-Ala-Glu, Phe-Ala-Leu, Ala-Glu-Leu, Ile-Ala-Pro-Gly, Val-Ala-Phe, and the heptapeptide Thr-Met-Glu-Pro-Gly-Lys-Pro, have demonstrated ACE-inhibitory activity in vitro, suggesting that microalgal peptides may contribute to antihypertensive effects relevant to cardiovascular health [59]. Phlorotannins from brown seaweeds such as *Ecklonia stolonifera* and *Ecklonia cava* have also been reported to show antihypertensive activity [48]. Seaweed polysaccharides also contribute to cardiovascular interest, and current reviews describe fucoidan as a brown-seaweed-derived hydrocolloid with antihypertensive and lipid-lowering effects, while also noting broader cardioprotective potential for other algal hydrocolloids [211]. Green seaweeds, such as

Ulva species, have been shown in rodent studies to lower plasma LDL cholesterol levels, supporting their potential for cardiovascular risk reduction [59]. In addition, sulfated seaweed polysaccharides are discussed for anticoagulant and antithrombotic properties, because they can interfere with coagulation pathways and therefore have potential relevance for thrombosis prevention [221]. Brown seaweed bioactives, such as phlorotannins, fucoxanthin, and phytosterols, have also been widely reviewed for their antioxidant and anti-inflammatory effects, which are relevant to endothelial protection and the prevention of atherosclerotic progression [209,210]. Algal carotenoids exert antioxidant effects by scavenging reactive oxygen species and protecting lipids, proteins, and DNA from oxidative damage, thereby helping to limit processes that contribute to cardiovascular disease [48]. In addition, algal carotenoids may enhance endogenous antioxidant defenses by modulating enzymes such as catalase and superoxide dismutase, thereby improving cellular redox balance [48].

Overall, the available evidence suggests that marine algal bioactives may support metabolic and cardiovascular health through interconnected effects on postprandial glucose control, lipid metabolism, adiposity, blood pressure regulation, oxidative stress, inflammation, endothelial protection, and gut microbiota-related metabolic pathways. However, the strength of evidence varies by compound class and health outcome, with many mechanisms still supported mainly by in vitro or animal studies. Future work should prioritize standardized algal preparations, clearly defined doses, longer randomized controlled trials, and safety evaluation so that promising metabolic and cardiovascular effects can be translated into reliable functional food, nutraceutical, or therapeutic applications [208,209,215,221,222].

11.3. Gut Health and Digestive Benefits

The gut microbiota plays a central role in digestion, immune function, and overall metabolic regulation [35]. Algae, particularly seaweeds, are recognized as promising gut-health ingredients because they provide substantial amounts of non-digestible polysaccharides and dietary fiber that can interact with the intestinal microbiota and its metabolic outputs [61]. Major algal polysaccharides, including alginate, laminarin, fucoidan, agar-derived polysaccharides, carrageenans, ulvan, and porphyran, are only partly digested by the host and can therefore reach the colon, where they become substrates for microbial fermentation and microbiota modulation [61,224]. Fermentation of these seaweed polysaccharides can promote the production of short-chain fatty acids, shift the Firmicutes/Bacteroidetes balance, and support beneficial microbes that support gut and metabolic health, although the fermentability of individual polysaccharides varies with structure, molecular weight, and sulfation patterns [61,115]. Human clinical trials have shown that fucoidan-rich extracts can improve gut microbial balance (promoting beneficial genera such as *Bifidobacterium* and *Faecalibacterium*) and reduce intestinal inflammation [145]. In a double-blind trial, a fucoidan extract from *Saccharina latissima* increased the relative abundance of healthy butyrate-producing gut bacteria and was associated with markers of reduced gut inflammation [145]. Because many algal polysaccharides resist digestion in the upper gastrointestinal tract, they reach the colon intact, where they function as prebiotics, selectively stimulating beneficial microbiota and promoting the production of short-chain fatty acids that contribute to gut and immune health [61]. One study noted that alginate and laminarin from brown seaweed, when consumed, altered the gut microbiota, increasing beneficial bacterial populations and the production of fermentative end products that nourish colonic cells [62]. Non-digestible oligosaccharides, abundant in macroalgae, are known to improve gut microbiota and, in doing so, may reduce the risk of colon cancer [64]. Additionally, sulfated polysaccharides derived from microalgae such as *Porphyridium* and

Chlorella may enhance mucosal immune function and promote the growth of beneficial gut microbiota through prebiotic activity [35].

Human evidence is emerging, and a study by Lopez-Santamarina et al. [225] involving a randomized double-blind placebo-controlled trial reported that daily intake of whole *Himanthalia elongata* beneficially modulated the gut microbiota of overweight adults by increasing several short-chain-fatty-acid-producing species, supporting its potential use as a functional prebiotic ingredient. Similarly, a recent double-blind, placebo-controlled trial showed that a fucoidan-rich extract from *Saccharina latissima* improved microbial diversity, increased beneficial taxa such as Bifidobacterium and Faecalibacterium, and enhanced pathways involved in short-chain fatty acid biosynthesis and carbohydrate metabolism in healthy adults [145]. Supplementation with *Undaria pinnatifida* has been shown to improve bowel regularity and stool output while increasing beneficial gut bacteria such as Bifidobacterium longum, supporting the prebiotic potential of kelp-derived polysaccharides, including fucoidans [59]. Alginate, along with laminarin and certain sulfated polysaccharides, has prebiotic effects by beneficially modulating the gut microbiome and enhancing short-chain fatty acid production in the colon, thereby supporting gut health and immunity [62]. Another randomized controlled trial in individuals with prediabetes found that fucoidan supplementation altered the gut microbiota composition and reduced inflammatory markers, including tumor necrosis factor-α, interleukin-6, and lipopolysaccharide, suggesting that some algal polysaccharides may support gut-associated metabolic and inflammatory regulation in humans [226]. Preclinical evidence also supports anti-inflammatory effects in the gut, and a study by Yi et al. [227] reported that dietary *Porphyra tenera* attenuated dextran sulfate sodium-induced colitis in mice by reducing disease activity, improving colonic histology, suppressing abnormal inflammatory responses, and modulating gut microbiota dysbiosis, along with changes in short-chain fatty acids and bile acids.

11.4. Anti-Cancer Properties

Cancer is driven by multiple genetic alterations that contribute to tumor initiation and progression, including enhanced angiogenesis, resistance to apoptosis, persistent proliferative signaling, deactivation of tumor suppressor genes, and increased metastatic potential of cancer cells [48]. One of the most actively investigated health benefits of algal bioactives is their anti-cancer potential, because marine macroalgae and microalgae contain structurally diverse metabolites that target multiple hallmarks of cancer in experimental models [228,229]. Recent reviews indicate that algal bioactives, particularly sulfated polysaccharides, phycobiliproteins, carotenoids, and phlorotannins, can suppress cancer cell proliferation, promote apoptosis, modulate oxidative stress and inflammation, and, in some cases, improve the response to standard anticancer therapy [228,230,231]. Among these compounds, fucoidan from brown seaweeds such as *Fucus vesiculosus*, *Undaria pinnatifida*, and other fucoid-rich species is one of the best-studied, with evidence of inhibition of cancer cell proliferation, induction of apoptosis, interference with epithelial-to-mesenchymal transition, and modulation of angiogenic and inflammatory signaling pathways [231,232]. More specifically, recent studies have reported that fucoidan-based treatments suppressed colorectal cancer proliferation and migration while inducing sub-G1 cell-cycle arrest and apoptosis, and that low-molecular-weight fucoidan also exhibited antiproliferative activity in melanoma models through Bcl-2- and PTEN/AKT-related mechanisms [233,234]. Fucoidan has also been investigated as an adjuvant or delivery component in combination therapy, including nanoparticle systems for triple-negative breast cancer and clinical supplementation studies in patients with rectal cancer, suggesting potential supportive benefits alongside conventional treatment, although stronger

clinical evidence is still needed [235,236]. Other sulfated polysaccharides from red algae, particularly carrageenans, have likewise shown anti-tumor activity, with reported effects including reduced cancer cell viability, induction of apoptosis, cell-cycle perturbation, and immunomodulatory actions that may be relevant to cancer control [228,237]. In addition, the red algal polysaccharide porphyran has been highlighted for its anticancer activity, including apoptosis, regulation of autophagy, anti-inflammatory effects, and immune modulation, making it a promising candidate for future chemopreventive or chemotherapeutic applications [237].

Algal phycobiliproteins, especially phycocyanin from cyanobacteria such as Spirulina, have also received attention because they can affect apoptosis, cell-cycle regulation, migration, and Wnt/β-catenin signaling in cancer-related models; phycoerythrin from red algae is also being explored, but the evidence base remains smaller than for phycocyanin [230,238]. Another important group is the brown algal polyphenols known as phlorotannins, which exhibit antioxidant, anti-inflammatory, and anticancer activities and have been reported to interfere with tumor cell survival, cell-cycle progression, apoptosis, oxidative stress, invasion, and metastasis-related pathways [111,239]. For example, phlorotannin-rich extracts from *Fucus vesiculosus* and *Ascophyllum nodosum* have shown selective cytotoxicity toward tumor cells and reduced reactive oxygen species linked to cancer progression, supporting their relevance as multifunctional nutraceutical candidates [240].

11.5. Immune Modulation and Anti-Inflammatory Effects

Algal bioactives are increasingly recognized for their ability to modulate immune responses and attenuate chronic inflammation, largely through bioactive polysaccharides, polyphenols, carotenoids, and peptides derived from both macroalgae and microalgae [209,241,242]. Seaweeds are particularly rich in compounds with immunoregulatory and anti-inflammatory activities, and recent reviews emphasize that these effects depend on algal species, extraction method, sulfation pattern, molecular weight, and dose [242,243]. Among the most studied immunomodulatory compounds are laminarin and fucoidan. These two brown algal polysaccharides have been associated with macrophage activation, modulation of cytokine signaling, and enhancement of innate immune responses, with fucoidan also attracting attention for its relevance to cancer immunotherapy [244,245]. Yang et al. [246] reported that fucoidans from *Ascophyllum nodosum* and *Fucus vesiculosus* enhance CD8+ T cell proliferation and activation by increasing IFN-γ and TNF-α secretion and upregulating JAK/STAT pathway-related genes, with evidence also suggesting interaction with the TCR/CD3 complex as part of the mechanism underlying fucoidan-induced immunomodulatory effects. EP2, a water-soluble polysaccharide derived from *E. prolifera*, has also been reported to exert immunomodulatory effects in cyclophosphamide-induced immunosuppressed mice [247]. Similarly, sulfated polysaccharide fractions from U. intestinalis exhibited strong immunomodulatory activity by stimulating pro-inflammatory cytokine production in J774A.1 cells macrophages, indicating their potential as natural immunomodulatory agents [248]. One randomized, double-blind, placebo-controlled trial in healthy adults found that supplementation with *Euglena gracilis* (a microalga rich in β-glucan) enhanced immune cell activity, including natural killer (NK) cell function, compared with placebo, suggesting improved immune responses with algal β-glucan intake [144]. Recent studies further indicate that seaweed polysaccharides can support antiviral defense not only by regulating host immune responses but also by interfering with viral attachment, adsorption, entry, and replication, thereby helping to explain the growing interest in these compounds as antiviral nutraceuticals and adjuncts [195,197,241]. Sulfated polysaccharides from red algae, especially carrageenans and related molecules, have shown inhibitory activity against enveloped viruses such as herpes simplex virus

and influenza virus, largely by blocking viral binding or early entry steps at the host cell surface [195,249].

Marine algal compounds are relevant in inflammatory contexts because persistent low-grade inflammation is a major feature of chronic disorders such as obesity, metabolic syndrome, cardiovascular disease, and inflammatory tissue injury [209,250]. Algal polyphenols and pigments, particularly phlorotannins and fucoxanthin, have been reported to suppress inflammatory signaling pathways such as nuclear factor kappa B (NF-κB) and MAPK and to reduce the production of inflammatory mediators, including TNF-α, IL-6, iNOS, cyclooxygenase 2 (COX-2), NO, and PGE2 in experimental models [99,251]. Fucoxanthin has also been described as a promising anti-inflammatory carotenoid in recent reviews, with evidence that it can mitigate obesity-associated inflammation and downregulate inflammatory responses in metabolically stressed tissues, although the strongest support remains preclinical [105,252]. Likewise, phlorotannins from brown algae have shown inhibitory effects on inflammatory enzymes and mediators, including COX-2 and lipoxygenase-related pathways, which supports their potential as naturally derived anti-inflammatory agents [99,253]. Human evidence is emerging but remains uneven: a recent meta-analysis by Mousavi et al. [254] reported that Spirulina supplementation significantly reduced CRP, IL-6, and TNF-α, whereas a review of randomized trials on whole seaweed consumption by Trigo et al. [255] concluded that human data on inflammatory markers are still limited and inconsistent. In addition, the antioxidant activity of algal bioactives indirectly supports immune function by limiting oxidative damage, preserving cellular function, and reducing redox-sensitive inflammatory signaling [99,209].

11.6. Neuroprotective Effects

Neurodegenerative disorders such as Alzheimer's disease and Parkinson's disease are driven by interconnected processes, including oxidative stress, neuroinflammation, mitochondrial dysfunction, and abnormal protein aggregation, and recent studies suggest that algae and algae-derived compounds show neuroprotective potential in experimental models by reducing oxidative stress and neuroinflammation, modulating apoptosis-related pathways, and supporting neuronal function [214–216]. Marine algal metabolites such as fucoidan, fucoxanthin, phlorotannins, sulfated polysaccharides, and omega-3 fatty acids are promising neuroprotective agents for disorders such as Alzheimer's disease and Parkinson's disease, although most evidence still comes from cell and animal studies [214–216]. These compounds appear to act through multiple pathways, including suppression of oxidative stress and neuroinflammation, preservation of mitochondrial function, attenuation of apoptosis, modulation of cholinergic signaling, and interference with pathogenic protein accumulation [256–258]. Among them, fucoxanthin from brown algae has received considerable attention for its ability to protect neural tissue against oxidative and inflammatory injury in experimental models [259,260]. In a recent study, long-term fucoxanthin treatment prevented cognitive deficits and reduced Aβ-related neuroinflammation in APP/PS1 transgenic mice, while also suppressing pro-inflammatory cytokine release and microglial activation [260]. Human evidence continues to emerge: a 12-week randomized, placebo-controlled trial using a *Phaeodactylum tricornutum* extract containing fucoxanthin reported improvements in selected cognitive outcomes among older adults with perceived cognitive decline [52]. Algal polysaccharides such as fucoidan have also shown neuroprotective potential by reducing oxidative stress, improving mitochondrial function, modulating neuroinflammation, and influencing the gut–brain axis in preclinical models [257,261]. For example, fucoidan has been reported to improve learning and memory-related outcomes in experimental models of cognitive dysfunction, including D-galactose-induced and other Alzheimer-like conditions [261,262].

In addition, marine-derived omega-3 fatty acids, especially DHA from microalgal oils, remain important for neuronal membrane structure and brain function. Recent systematic review evidence suggests that DHA supplementation may provide cognitive benefits in some individuals with early cognitive decline, although results remain inconsistent across trials [130,263]. Brown algal phlorotannins are also relevant because compounds such as eckol, dieckol, and 8,8′ bieckol have shown inhibitory activity against acetylcholinesterase and, in some cases, beta-site amyloid precursor protein cleaving enzyme 1 (BACE1), supporting their possible usefulness against cholinergic dysfunction and amyloid-related pathology in Alzheimer's disease [258]. The red alga *Neorhodomela aculeata* has been identified as a potential neuroprotective and anti-inflammatory agent for the management of age-related neurological disorders [64].

11.7. Bone Health

Marine algae are increasingly being investigated for bone health because they provide minerals and bioactive compounds that may support bone formation, mineralization, and skeletal health [264,265]. Certain algae, especially mineral-rich red algae such as *Lithothamnion* species, are recognized as natural sources of calcium, magnesium, and multiple trace minerals that are relevant to bone composition and density [223–225]. Recent work on marine-derived mineral ingredients has further shown that seaweed-based multimineral products can provide substantial calcium content together with a broad trace mineral profile, and these formulations have been studied as alternatives to conventional mineral supplements [266,267]. Evidence from recent bioaccessibility research indicates that seaweed-derived calcium-containing products, such as Aquamin F, are designed to improve mineral availability and were well tolerated in older adults in a randomized, placebo-controlled study, although this does not, by itself, establish long-term fracture or osteoporosis outcomes [267].

Preclinical evidence is also encouraging, as a recent systematic review and meta-analysis by Saleng et al. [268] concluded that seaweed compounds may facilitate bone growth. However, the authors emphasized that the number and quality of available studies remain limited. In addition to their mineral contribution, seaweed polysaccharides such as fucoidan and ulvan have attracted attention in bone research for promoting osteogenic differentiation, supporting osteoblast adhesion and proliferation, and modulating inflammatory signaling pathways involved in bone repair and regeneration [264,269]. Algae-derived molecules may influence the balance between bone formation and bone resorption, which is central to disorders such as osteopenia and osteoporosis [264]. For this reason, marine algae are being explored not only as nutritional sources of bone-related minerals but also as sources of osteoactive compounds for functional foods, biomaterials, and future adjunctive strategies against bone loss [265].

12. Sustainability, Biorefinery Value, and Economic Outlook for Marine Algal Bioactives

Marine algae are increasingly positioned as sustainable platforms for producing bioactive compounds and functional ingredients because marine microalgae are described as biofactories for high-value compounds used in health, cosmetics, and functional foods, while marine macroalgae are described as third-generation biomass for pigments, sulfated polysaccharides, rare sugars, oligosaccharides, and other compounds with pharmaceutical, nutraceutical, and cosmetic relevance [1,12]. Microalgae are also discussed as sustainable protein and biomass sources because they can grow on non-arable land, use saline water, wastewater, or industrial effluents, and require substantially less land than livestock and soy protein systems, although environmental performance depends strongly on the cultivation

technology and energy inputs used [270]. These resource advantages are relevant to marine algal bioactives because production systems that lower land and freshwater demands can support more sustainable supply chains for compounds such as pigments, PUFAs, proteins, polysaccharides, and specialty ingredients [1,270]. Microalgae can contribute to circular production models because recent reviews highlight their high photosynthetic efficiency, capacity for biological CO_2 capture, and product versatility, which enable the conversion of carbon streams into biofuels, bioactive compounds, and high-value chemicals [31,271]. Integrated microalgal biorefineries are being evaluated as circular economy systems because their commercial viability depends on coordinated cultivation, harvesting, processing, product recovery, techno-economic performance, and life-cycle outcomes rather than on biomass production alone [31]. Wastewater and effluent-based cultivation are also relevant to algal sustainability because microalgal systems can use nutrient-rich waste streams while producing biomass that may be directed toward proteins, pigments, lipids, and other value-added fractions, although harvesting and downstream processing remain important cost and energy barriers [42,270]. Seaweed-based integrated multi-trophic aquaculture is similarly discussed as an approach to improving aquaculture sustainability, as seaweed can serve as extractive organisms that retain nutrients and reduce environmental pressures in integrated systems [272,273].

The economic value of marine algae is closely linked to biorefinery strategies, as macroalgae are reported to contain multiple high-value compounds, including pigments, sulfated polysaccharides, rare sugars, and oligosaccharides, and biorefinery pathways are being developed to improve extraction and valorization for food, pharmaceutical, nutraceutical, and cosmetic applications [12]. Macroalgae biorefineries are also presented as a route to obtain carrageenan, proteins, lipids, pigments, biostimulants, and biofuels from the same biomass, although their profitability depends on production yields, resource demand, environmental performance, and technical feasibility at scale [18]. At the firm and technology levels, techno-economic analyses indicate that algae commercialization is most viable when biomass is directed toward high-value applications, such as nutraceuticals, pigments, proteins, and specialty bioactive compounds, rather than low-value bulk products, such as biofuels [274]. This has led to increasing emphasis on the biorefinery concept, in which algal biomass is fractionated into multiple value-added products to improve overall process efficiency and economic feasibility. In this context, algae-based biofuels remain economically challenging when produced as standalone products, whereas co-producing high-value bioactive compounds can significantly enhance overall returns and support commercialization [274]. For microalgae, integrated biorefineries are considered important because single-product biofuel production remains economically challenging, whereas co-producing high-value compounds can improve overall process feasibility [32]. Recent benchmarking studies also emphasize that large-scale microalgal biorefineries face major challenges with harvesting and processing costs, making value-added fractions and efficient downstream recovery central to economic viability [42]. Recent techno-economic and life-cycle studies provide additional quantitative support for this biorefinery-oriented approach. For microalgae, combined processing models show that profitability and sustainability improve when biomass fractionation, product recovery, coproduct valorization, and life-cycle performance are considered together rather than separately [275]. Similarly, an integrated life-cycle and techno-economic assessment of microalgal systems indicates that recovering coproducts, such as biofertilizers, can improve overall process value and should be incorporated into early process design [276]. For macroalgae, techno-economic assessment of biorefinery scenarios shows that economic performance depends strongly on the selected product portfolio, operating cost, revenue structure, and conversion of biomass into multiple value-added streams [277]. These studies strengthen the argument that ma-

rine algal bioactives should be developed within multiproduct processing systems instead of single-output production models. Quantitative techno-economic studies further show that algal biorefinery economics are strongly influenced by scale, moisture handling, utility demand, and investment performance. In a National Renewable Energy Laboratory (NREL) open-pond microalgae design case, the minimum biomass selling price decreased from US$576–649 t^{-1} ash-free dry weight (AFDW) for 2-acre pond systems to US$392–419 t^{-1} AFDW for 50-acre pond systems, showing the importance of cultivation scale and pond design [278]. For the representative 10-acre base case, the same study reported a total capital investment of US$390.2 million, a variable operating cost of US$27.06 million y^{-1}, a fixed operating cost of US$11.69 million y^{-1}, an average electricity demand of 9753 kW, and fossil energy consumption of 8.8 MJ kg^{-1} AFDW biomass. In a large-scale *Dunaliella tertiolecta* cultivation study, operating cost decreased from US$3.19 L^{-1} at laboratory scale to US$0.77 L^{-1} at large scale, while a 1-ha facility had a capital investment of US$82,019.89, net present value of US$750.91, internal rate of return of 5.18%, and payback period of 7.76 years [279]. In macroalgae, an *Ulva rigida* biorefinery TEA using 50,000 kg h^{-1} wet seaweed feed estimated investment costs of US$22.25 million for acetone-butanol-ethanol production and US$25.71 million for bioethanol production, with annual production costs of US$54.00 million and US$44.35 million, respectively [277]. Utilities were the dominant operating-cost component in the same *Ulva* study, accounting for US$38.09 million y^{-1} in the acetone-butanol-ethanol route and US$31.61 million y^{-1} in the bioethanol route, and the acetone-butanol-ethanol route had a discounted payback period of 4.11 years at a base seaweed price of US$21 t^{-1} [277]. These quantitative benchmarks indicate that future marine algal biorefinery studies should report capital expenditure, operating expenditure, energy consumption, utility cost, minimum selling price, net present value, internal rate of return, payback period, and sensitivity analysis alongside extraction yield, product purity, and life-cycle performance [277–279].

Market trends further support the economic relevance of marine algal bioactives and algae-derived products because the UN Trade and Development reported that global seaweed production tripled from 11.9 to 36.3 million tonnes between 2002 and 2022, while exports quadrupled to $3.9 billion [280]. The same report noted that aquaculture accounted for 97% of seaweed production and that Asia accounted for 98% of global output, indicating that supply remains highly concentrated despite growing global demand. Value-added products such as agar, carrageenan, and alginic acid generate higher returns than raw seaweed, supporting the economic argument for processing marine algae into extracted compounds and functional ingredients rather than relying solely on unprocessed biomass [280]. In Europe, the algae sector is receiving increasing institutional support, as the European Union invested more than €559 million in 219 algae-related projects between 2014 and 2023 to scale algae innovation across food, renewable energy, marine restoration, bioplastics, and other applications [281]. Accordingly, the sustainability and economic outlook for marine algal bioactives depend on integrating low-resource cultivation, circular use of nutrients and carbon, efficient extraction, and biorefinery-based recovery of high-value compounds [12,31,42].

13. Challenges, Limitations, and Future Perspectives

A primary limitation is biomass inconsistency, because recent food-design reviews identify inconsistent methods of characterizing microalgal biomass as a major obstacle to large-scale competitiveness, and seasonal and site-related differences in Ulva biomass were shown to shift the content and relative proportions of target polyphenols, chlorophylls, and carotenoids, with downstream effects on antioxidant activity and technological behavior [13,282]. This variability makes standardized ingredients difficult to obtain, un-

derscoring the need for optimized extraction and encapsulation procedures to generate more uniform and reproducible bioactive profiles [13].

At the extraction stage, recent studies emphasize that conventional extraction techniques largely fail to adequately address seaweed complexity, while yield and selectivity remain strongly dependent on pretreatment, solvent choice, temperature, and biomass-to-solvent ratio [11]. For this reason, future work is expected to prioritize target-specific optimization and greener intensified extraction strategies that preserve thermolabile metabolites while improving selectivity and environmental performance [11].

Scalability remains another central bottleneck, as microalgal biorefineries continue to be constrained by costly, energy-intensive harvest and processing stages, while open ponds and closed photobioreactors face a persistent trade-off between lower capital costs and higher contamination risk, and greater process control with higher capital and operating expenditure [42]. In autotrophic systems, low biomass concentrations and high water content make harvesting long, expensive, and energy-intensive, and the harvest and processing stages may account for approximately 20–30% of total operating expenditure [42].

Formulation is equally decisive for translation, since *Ulva*-derived bioactives were reported to have low chemical stability, poor oral bioavailability, and undesirable sensory traits, whereas encapsulation by spray drying or freeze drying with suitable biopolymer carriers improved stability, resistance to environmental factors, shelf-life-related properties, and powder handling [13].

The evidence base in humans is still comparatively thin, because studies with pure algal metabolites were described as scarce and largely limited to kahalalide F and fucoxanthin, while most clinical studies assessed algae as extracts, fractions, or whole-consumption interventions rather than as rigorously characterized individual compounds [283].

Regulatory translation also remains demanding, because legislation and consumer acceptance were identified as factors separating laboratory innovation from industrial implementation, and EFSA-oriented novel-food evaluation of microalgae-derived products requires strain-level taxonomic identification, chemical and microbiological characterization, nutritional characterization, manufacturing-process description, and toxicological and allergenicity assessment [30,282].

Recent systems analyses therefore favor integrated, closed-loop, multi-product biorefineries, because coupling energy products with higher-value fractions and integrating multiple unit operations can improve recovery, process efficiency, and profitability, while lower-energy harvesting, renewable electricity, and water recycling have been identified as practical routes to reduce environmental and economic burdens [20,42].

As a concise future perspective, marine omics-assisted bioprospecting offers a credible route to expand the discovery pipeline, because transcriptomics, proteomics, and computational approaches can screen thousands of molecules, enrich bioactive databases, predict molecular targets and mechanisms, and help identify candidate biosynthetic enzymes and sequences relevant to industrial scale-up in poorly annotated marine organisms [5].

Together, these limitations indicate that future research should shift from broad bioactivity screening to application-oriented development pipelines that integrate biomass standardization, compound recovery, translational validation, safety, and scale-up feasibility. Standardized biomass-provenance reporting should become routine, including algal species, strain or voucher identity, production or collection site, harvest period, cultivation conditions, pretreatment, drying method, storage, and processing history, because algal composition and bioactivity are strongly affected by source conditions and processing, while the algae sector continues to face traceability, regulatory, market, and scale-up barriers [13,282,284]. Extraction studies should also prioritize target-specific green processing coupled with compound-level characterization, using chromatographic, spectroscopic,

molecular-weight, and omics-based tools to link defined fractions and structures with mechanisms of action rather than relying primarily on crude-extract activity [5,11,285]. Translational studies should evaluate bioaccessibility, bioavailability, formulation compatibility, shelf-life stability, sensory acceptability, and efficacy in relevant in vitro, animal, and human models, since current evidence often relies on whole algae, extracts, or incompletely characterized fractions rather than purified or well-defined algal metabolites [13,283]. Safety and regulatory readiness should be integrated early through taxonomic verification, contaminant monitoring, toxicological testing, allergenicity and sensitization assessment, dose justification, microbiological characterization, and product-specific quality specifications, particularly because algae-derived products may require evaluation for iodine, arsenic species, cadmium, lead, mercury, and other safety concerns, depending on source and intended use [30,282,285]. Scale-up research should combine pilot-scale processing with techno-economic analysis and life-cycle assessment to evaluate recovery yield, energy demand, coproduct valorization, greenhouse gas outcomes, cost structure, and market fit within realistic multiproduct biorefinery pathways [20,42,275]. This integrated approach would provide a stronger basis for determining which marine algal bioactives can be translated into reproducible, safe, economically viable, and application-ready products.

14. Conclusions

Marine algae represent a highly valuable and chemically diverse resource for the development of bioactive compounds with applications across food, pharmaceutical, cosmetic, agricultural, aquaculture, environmental, and broader biotechnological systems. This review highlights that both macroalgae and microalgae produce functionally important compounds, including sulfated polysaccharides, carotenoids, phenolic compounds, phlorotannins, proteins, peptides, sterols, vitamins, MAAs, and PUFAs. These compounds are not only structurally diverse but also biologically relevant, with reported antioxidant, anti-inflammatory, antimicrobial, antiviral, metabolic, immunomodulatory, and skin-protective properties. Their activity is strongly influenced by compound structure, algal source, extraction conditions, molecular size, sulfation pattern, polymerization, lipid composition, and interactions with biological systems.

A major strength of marine algal bioactives is their ability to connect natural product discovery with practical product development. Advances in biotechnological cultivation, stress-induced metabolite production, green extraction, purification, analytical characterization, and formulation strategies have improved the recovery and functional use of algal bioactive compounds. These developments are especially important because the value of algal bioactives depends not only on their biological activity but also on their stability, bioaccessibility, bioavailability, safety, sensory acceptability, regulatory status, and performance in real product systems. The application sections further demonstrate that algal bioactives can support the development of functional foods, nutraceuticals, pharmaceutical materials, cosmeceuticals, aquafeeds, biostimulants, and environmental remediation approaches, reinforcing their role as multifunctional resources in sustainable bioeconomy systems.

Despite this potential, several barriers still limit the full translation of marine algal bioactives from laboratory studies to commercial products. Variability in algal biomass composition, inconsistent extraction methods, limited standardization, poor bioavailability of some compounds, incomplete clinical validation, safety concerns related to contaminants, regulatory differences, and scale-up costs remain important challenges. Future progress will depend on integrated strategies that combine standardized biomass sourcing, target-specific extraction, advanced characterization, improved delivery systems, controlled cultivation, biorefinery-based processing, and stronger human or application-specific validation. Integration of omics-driven bioprospecting, metabolite profiling, and pathway-level

characterization may further improve the discovery of novel algal compounds and support strain selection for high-value production. Economic feasibility should also be considered from the earliest stages of development because commercial success depends on reducing cultivation, harvesting, dewatering, extraction, purification, stabilization, and energy costs while increasing product yield, coproduct value, process efficiency, market fit, and regulatory readiness. Overall, marine algae offer a strong platform for the sustainable development of bioactive compounds, but their wider adoption will require coordinated efforts integrating compound discovery, mechanistic understanding, technological processing, safety assessment, and scalable industrial applications.

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