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Pharmacological Potential of Marine Algae: A Review of Bioactive Compounds and Therapeutic Applications

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Abstract

Background: Marine algae, ranging from microscopic microalgae to larger seaweeds, have been the subject of much attention in recent years due to their nutraceutical and pharmacological value. They are broadly classified into four classes - brown algae (Phaeophyta), green algae (Chlorophyta), red algae (Rhodophyta) and blue-green algae (Cyanophyta), having their own pigments and metabolic pathways. These taxonomic differences are important to identify species that produce specific bioactive compounds, such as well-known metabolites such as carrageenan, fucoidan, astaxanthin and phlorotannins. **Aim:** The aim of this review is to explore the biochemical composition, taxonomy, and extraction methods of marine algae, and to focus on the therapeutic potential and relevance to pharmaceutical, cosmetic and biomedical applications. **Methods:** The published literature on algae-derived bioactive substances such as polyphenols, polysaccharides, proteins, pigments, sterols and lipids and their related biological effects was reviewed. The review also explores emerging biotechnological approaches, such as enzyme-assisted extraction, strategies to increase metabolite yield, and CRISPR-based methods for improving therapeutic utility. **Results:** Bioactive compounds from marine algae display a wide range of biological activities such as anti-inflammatory, antioxidant, anticancer, antimicrobial, cardioprotective and antiviral activities. Therapeutic suitability is closely related to the pigment and metabolite composition characteristic of each taxonomic group. Advances in extraction technology and biotechnology are enabling incorporation of these compounds into nanoformulations and targeted drug-delivery platforms, expanding opportunities in drug development. **Conclusion:** Marine algae are sustainable, eco-friendly alternatives to synthetic pharmaceutical agents, with lower toxicity and good bioavailability. However, there are still obstacles in areas like standardisation of cultivation, regulatory safety frameworks, clinical validation and omics-based research, indicating the need for well-structured sustainable aquaculture systems. Marine algae, in the end, represent a valuable and disruptive asset in the bio-economy and have great potential for future therapeutics from natural products.

Major Finding: Marine algae are sustainable, rich sources of diverse bioactive compounds with broad therapeutic potential, and advances in biotechnology and nanotechnology are accelerating their application in modern drug development, despite challenges in standardisation and clinical validation.

Keywords: Algal Extraction Methods, Anti-inflammatory, Antimicrobial, Marine Algae, Neuroprotection, Phlorotannins

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1. Introduction

Marine algae, generally referred to as seaweeds, are a diversified group of photosynthetic organisms that thrive primarily in the marine environment[1]. They are generally categorised based on their pigment composition as green, red and brown algae. They function as primary producers and play an important ecological role by contributing substantially to globalised production of oxygen and sustaining marine food chains[2]. Their effective carbon dioxide absorption highlights their significance in the regulation of climatic conditions. Apart from

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their ecological role, marine algae are a rich source of polyphenols, fatty acids, pigments, polysaccharides and other bioactive compounds. The investigation of these substances will enable outreach in targeted research and increase the therapeutic value of anti-inflammatory, antioxidant, anticancer, and antimicrobial effects. Such properties sparked growing interest in the improvement of algae-based pharmaceuticals, nutraceuticals and functional foods. They are consumed in several coastal cultures because of their abundance of minerals, fibre, and important vitamins. Various kinds of marine algae serve as a renewable source of valuable hydrocolloids such as *agar, alginate* and *carrageenan* that are generally used as gelling agents, emulsifiers and stabilisers in the cosmetic and food products[3]. In addition, their minimal cultivation and rapid growth make them highly suitable for the production of biofuel and environmental applications that include pollution and management of the wastewater. The marine algae represent to underexplored due to their importance as valuable biological resources across nutritional, medicinal and industrial domains.

Marine algae that encompass red, green and brown varieties are under more research in the biomedical field because of their enriched bioactive component. Such marine organisms develop an array of secondary metabolites like phlorotannins, polysaccharides, pigments, peptides and alkaloids that demonstrate substantial therapeutic impacts[4]. Such biological actions comprise antiviral, anti-inflammatory, antimicrobial, and anticoagulant activities, positioning them as a significant candidate for the development of novel therapeutics. Figure 1 is a picture representing brown and green algae[5].

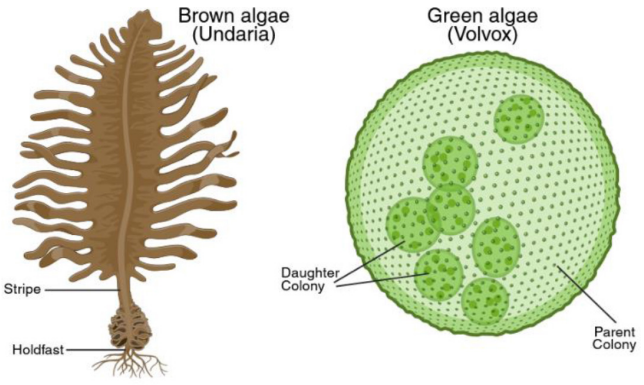


Figure 1. Brown and green algae[5].

Among the most noticeable sulphated polysaccharides such as carrageenan, ulvan and fucoidan, which have the characteristics for inhibition of tumour progression, interference with and stimulation of immune responses with viral life cycles. The fucoidans depicted the potential for the promotion of programmed cell death and decreasing the spread of cancer, whereas the carrageenan is assessed as a topical agent for the prevention of infections like HPV and HIV[6]. In addition, the algal polyphenols combat oxidative stress, which is a key factor in several degenerative diseases, that provides cardioprotective and neuroprotective benefits. The biomaterials that were extracted from algae like *agar* and *alginate* are used extensively in wound healing, tissue engineering and regulated drug delivery systems with their gel-forming and biocompatibility abilities[7].

Figure 2 presents the steps of microalgae cultivation methods. Further, some of the marine algal compounds are efficient against the resistant bacterial strains, which makes them useful in addressing the increasing threat of antimicrobial resistance[8-10]. Marine algae have sustainable growth, rich chemical diversity, and a minimal ecological footprint[11]. With sustained scientific exploration, the organisms inspire nature-based innovative and biomedical solutions for various global health concerns.

2. Scope and Objectives of the Review

Microalgae are recognised increasingly as an important source of bioactive materials with importance to pharmacological research and the development of



Figure 2. The microalgae cultivation methods: Photoautotrophic, heterotrophic, photoheterotrophic, and mixotrophic methods[8].

drugs. Several investigations focused on the medicinal characteristics of the algae-derived components from *Arthrospira, Chlorella vulgaris*, *Dunaliella salina,* Nostoc, *Haematococcus pluvialis and Botryococcus braunii.* The species develop an extensive range of biologically active molecules that exhibit potent antimicrobial, antiviral, antifungal, anticoagulant, anti-inflammatory, anticancer and antioxidant effects. Certain species are able to fold proteins into complex 3D models for the synthesis of therapeutic proteins. Noticeably the research demonstrated the successful production of biological drugs and antibodies derived from algae for treating pulmonary emphysema. Specifically, *Chlamydomonas reinhardtii* is a vital microalga with a high level of applications for both veterinary and human usage. The ongoing discovery of such high-value bioactives from green algae is considered a promising advance for pharmaceutical innovation. Furthermore, Nostoc is useful as a dietary supplement because of the abundance of lipids, proteins and fatty acids. The clinical efficacy has also been documented in treating conditions like fistulas and some types of cancer that further validates the therapeutic potential of microalgae. This review explores the huge pharmacological potential of marine algae by focusing on their rich diversifies constituents and extensive therapeutic impacts. This provides a deep analysis of several compounds observed in the marine macroalgae and analyses their roles in disease prevention and health.

By organising scientific findings, the paper emphasises the biological activities of these compounds, including their antioxidant, antimicrobial, antiviral, anticancer, anti-inflammatory, and anticoagulant properties. Additionally, the review discusses their applicability in pharmaceuticals, functional foods, and nutraceuticals, while highlighting environmentally friendly aspects such as sustainability and renewability. It also reviews extraction techniques and structural features of key compounds, offering insights into their mechanisms of action. Finally, the paper outlines current knowledge gaps and suggests future directions for research, positioning marine algae as a promising and underutilised source for bioactive molecules in the advancement of biomedical science and human health.

3. Classification of Marine Algae

The marine algae are a more diverse group of photosynthetic organisms that thrive in the oceanic habitats and are divided broadly into *microalgae* and macroalgae[12]. This classification has been primarily based on their morphology, size and ecological function, with every group playing important roles in the marine ecological system and providing distinct biotechnological and industrial challenges. The macroalgae that are commonly known as the seaweeds are multicellular, large forms of algae which are highly visible. Such large multicellular algae are generally

Table 1. Macroalgae - classification

Type	Scientific Name	Pigment and Colour	Key Features
Green algae	*Chlorophyta*	Chlorophyll a and b (bright green)	Found in shallow waters; includes edible species like *Ulva* (sea lettuce)
Brown algae	*Phaeophyta*	Fucoxanthin (brown/yellow-brown)	Includes kelp; forms underwater forests; rich in alginates
Red algae	*Rhodophyta*	Phycoerythrin (red/purple)	Can grow at greater depths; source of agar and carrageenan

Table 2. Classification of microalgae

Type	Examples	Characteristics
Diatoms	*Navicula*, *Thalassiosira*	Silica cell walls; major oxygen producers
Dinoflagellates	*Ceratium*, *Noctiluca*	Some are bioluminescent; can cause red tides
Cyanobacteria (Blue-green algae)	*Spirulina*, *Nostoc*	Technically bacteria; photosynthetic organisms; used in supplements
Green microalgae	*Chlorella*, *Dunaliella*	High in proteins and pigments; used in biofuel and nutrition

observed in the coastal waters, and the classification is presented in Table 1[13,14].

The taxonomic identification of the macroalgae is generally based on the cellular wall composition, pigment profile and reproductive structures, that remains key elements in classical taxonomy through molecular tools such as 18S rRNA and rbcL sequencing, which are now used for confirmation, where sunlight is more abundant. In contrast to higher plants, they do not have vascular tissues but possess differentiated parts like blades, holdfasts and stipes that mimic leaves, roots and stems, respectively[15]. Macroalgae are important as primary producers ecologically and play a prominent role in habitat structuring and nutrient cycling. Ecologically, macroalgae are important producers and play a prominent role in habitat structuring and nutrient circulation.

Ecologically, macroalgae are vital as primary producers and play a role in habitat structuring and nutrient cycling. From a practical standpoint, they are valuable sources of food (such as nori and wakame), and produce industrially significant hydrocolloids like alginate, carrageenan, and agar. Moreover, their bioactive compounds are being explored for their potential use in pharmaceuticals and nutraceuticals[16]. In general, microalgae are microscopic, colonial or unicellular organisms that inhabit both the freshwater and marine environments. These groups include several taxa like diatoms, cyanobacteria, unicellular green algae, and dinoflagellates. In spite of their size, the microalgae are prolific incredibly that serves as the foundation of aquatic food chains by forming the *Phytoplankton* community. They are considered the main contributors of global oxygen production and play a crucial role in fixing carbon[17]. Despite a lack of structural complexity, the rapid growth, high metabolic stress and adaptability make them suitable for cultivation on a large scale[18]. The microalgae classification with its features is presented in Table 2[17,18].

Each kind has a specific role in the marine ecological system in the production of oxygen, carbon fixation to serve as medicine, food and industrial raw materials. Both microalgae and macroalgae contribute to environmental functions like carbon sequestration and O2 generation, and their application vary substantially. Macroalgae are specific for direct consumption and bulk harvesting, whereas each algal group represents the importance of marine biodiversity with important ecological and commercialised ability[19]. The understanding of the peculiar capabilities and traits is necessary for advancing sustainable techniques in energy, health and environmental sectors, that could be viewed in the following Figure 3[20].

4. Taxonomic Classification and Diversity

Marine algae encompass an extensive range of photosynthetic organisms observed in aquatic environments and taxonomically diversified across

Table 3. Taxonomic classification and diversity of Marine algae

Group	Taxonomic classification	Dominant pigments	Stored compounds	Representative genera
Green algae	*Chlorophyta* (Class: Ulvophyceae)	Chlorophylls a and b (bright green colouration)	Starch-based energy reserves	*Ulva*, *Caulerpa*
Brown algae	*Ochrophyta* (Class: Phaeophyceae)	Fucoxanthin with chlorophylls a and c (brownish hue)	Laminarin and mannitol	*Sargassum*, *Laminaria*
Red algae	*Rhodophyta*	Chlorophyll a and phycoerythrin (red to purplish tint)	Floridean starch	*Gracilaria*, *Porphyra*
Diatoms	*Bacillariophyta*	Chlorophylls a and c, and fucoxanthin (golden-brown)	Chrysolaminarin	*Navicula*, *Thalassiosira*
Dinoflagellates	*Dinophyta*	Chlorophylls a and c, with peridinin (reddish-brown)	Starch	*Ceratium*, *Noctiluca*
Cyanobacteria	*Cyanophyta* (blue-green algae)	Chlorophyll a, phycocyanin, phycoerythrin (blue-green pigments)	Cyanophycean starch	*Spirulina*, *Nostoc*

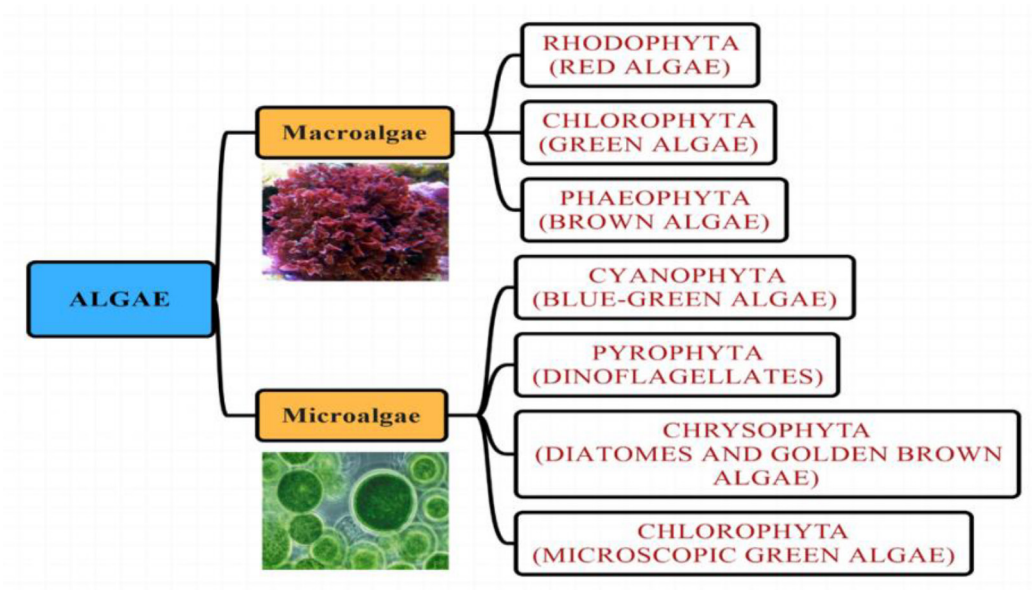


Figure 3. A broad classification of the algae.

multiple kingdoms, as presented in Table 3, which includes Chromista, Bacteria, and Plantae. They are distributed across various phyla-based features like storage materials, pigmentation and structural complexity[21]. The cyanobacteria are prokaryotic and photosynthetic, and Nostoc and Spirulina have high therapeutic and nutritional value. Table 3 shows the Taxonomic classification and diversity of Marine algae[21,22].

In terms of diversity, the marine algae differ in establishing accurate taxonomic identity, which is important for linking the chemical variation to biological actions. Misclassification could lead to inconsistent pharmacological outcomes, which underscores the requirement for molecular taxonomy in algal research from algae like Chlorella to kelp. They inhabit an extensive range of marine environments from intertidal zones to cloudy deep oceans[22]. Functionally, they serve as the major producers that support marine biodiversity and produce half of the oxygen.

To address this, robust modelling tools are required for the identification of key environmental factors that drive invasions for the prediction of both the future and current distribution patterns. These studies are important for the management of biological invasions and the formulation of emerging environmental disputes. This paper highlights the taxonomic expertise and the challenges exposed by the cryptic species, which is important for analysing or forecasting biological invasions that begin with the accurate taxonomic assessment[23].

5. Bioactive Compounds in Marine Algae

Marine algae are a valuable source of diverse bioactive molecules with considerable therapeutic and nutritive applications. The polysaccharides like alginate, carrageenan and fucoidans are specifically noteworthy for their anticoagulant, antiviral, immune-enhancing, and antioxidant properties. They are observed mainly in red and brown algae; they have gained interest in pharmaceutical and functional food development. The flavonoids and polyphenols, especially phlorotannins from brown algae, are well documented for their anti-inflammatory and antioxidant effects and act against chronic illness. Marine algae also synthesise peptides and proteins that include bioactive peptides and enzyme inhibitors that demonstrate antihypertensive and anticancer activities, that shows potential in cancer and cardiovascular treatments. Additionally, pigments such as astaxanthin and fucoxanthin provide not only antioxidant benefits but supports obesity management and skin health, with developing usage in the nutraceutical and cosmetic industries[24]. The sterols and lipids have more neuroprotective and cardiac protective characteristics. The compounds generally derived from the microalgae serve as the best

eco-friendly alternatives to fish-based oils. They are increasingly identified for their role in the development of future health-promoting products and innovation in the biomedical field. The following Figure 4 represents marine algae as potential anticancer drugs[25].

5.1 Polysaccharides

The polysaccharides are important nutritional elements that are found in all the algal species that functions as the major energy reserve. Based on their structural complexity and molecular size that are classified as disaccharides, monosaccharides and polysaccharides. Xie and Cheong[25] determined glucose, mannose, galactose, xylose, fucose and arabinose as the general monosaccharides. Dobrinčić[26] analysed the extraction methods as well as the structural and isolation details of MAPs from the marine species. In addition, Premarathna *et al.*[27] analysed the various extraction techniques that influence the physicochemical characteristics and the antioxidant activity of the polysaccharides and the hydrogels that were derived from them. Ummat *et al.*[28] signified the pre-treatment performed before the extraction process, and Hwang *et al.*[29] suggested improvements in the extraction of bioactive compounds like polysaccharides that involve the shifting from traditional water- to organic solvent-based methods for enzyme-assisted extraction methods that provide the advantages of reduced energy consumption and enhanced quality of the extracted metabolites. Yao *et al.*[30] highlighted the structural diversity of the polysaccharides and their differing impacts that depend on the algal category, where Akter *et al.*[31] outlined the specific polysaccharides with reference to biomedical applications, especially highlighting their antimicrobial potential.

5.2 Polyphenols and Flavonoids

The phenolic compounds are important secondary metabolites that enable marine organisms to survive and defend themselves in competitive habitats. Getachew *et al.*[32] highlight the macroalgae utilisation of these compounds for withstanding environmental challenges such as UV radiation, oxidative and herbivory stress. Yesiltas *et al.*[33] promptly determined an extensive array of phenolics in the green, brown and red algae. Figure 5 represents the Schematic representation of the extraction, purification, structural characterisation, biological functions, and applications of marine algal polysaccharides[34].

The identified compounds exhibited diverse biological activities, including antioxidant and antibacterial properties[34], while biosynthesised silver nanoparticles derived from red algae demonstrated promising biological effects in animal studies[35], and

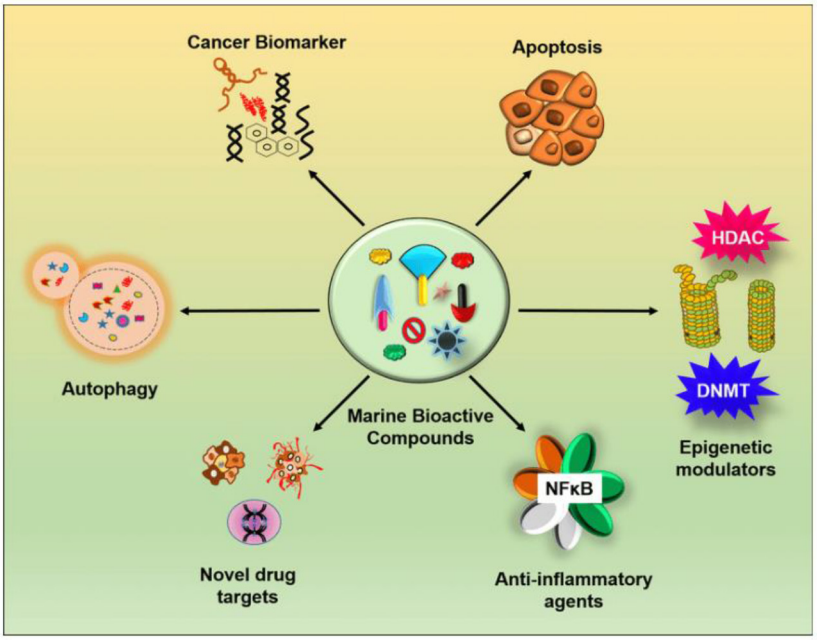


Figure 4. Bioactive compounds from marine algae as potent anticancer drugs.

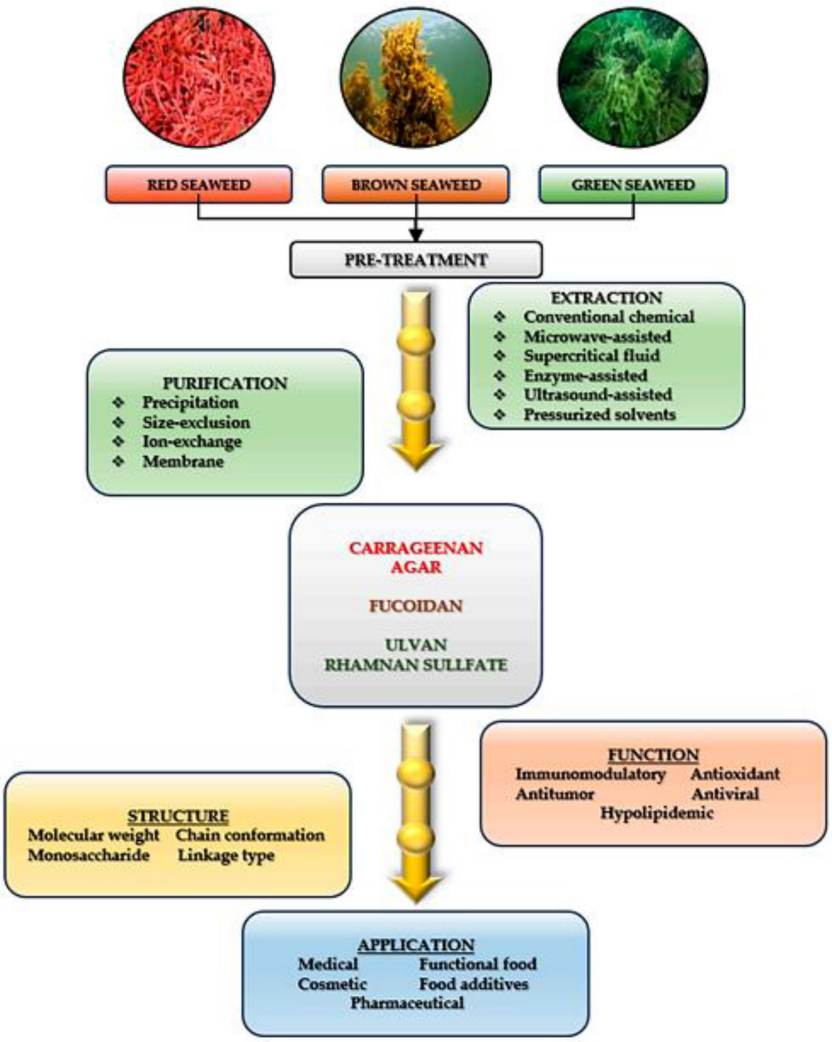


Figure 5. Schematic representation of the extraction, purification, structural characterisation, biological functions, and applications of marine algal polysaccharides.

Vijayan *et al.*[36] presented their thylakoid membrane remodelling.

5.3 Proteins and Peptides

Marine microalgae are rich in proteins that make them highly valuable in nutraceutical, food and animal feed sectors. With reference to the research by Cadar *et al.*[37], seaweeds could contain fifty per cent of protein by dry weight that includes several bioactive components such as enzymes, peptides, lectins, glycoproteins with mycosporine-like structures and phycobiliproteins. Dhaouafi *et al.*[38] highlighted that macroalgae, underscored the red seaweeds, contain essential amino acid contents. Beyond nutrition, the algal proteins exhibited functional benefits. Rawiwan *et al.*[39] and Fleurence[40] noted that the non-protein nitrogen elements such as pigments and nitrites could inflate protein estimates because of the standardised nitrogen-to-protein conversion factor of 6.25. Table 4 shows the peptides and peptides from the microalgae supporting studies[41].

5.4 Pigments (Carotenoids and Phycobiliproteins)

Algal pigments synthesised as secondary metabolites are famous for their therapeutic characteristic and the versatility across pharma, food and cosmetics. Manzoor *et al.*[41] correlated these pigments with anti-inflammatory, antioxidant and neuroprotective impacts. The three main classes of marine pigments are carotenoids, chlorophylls and the phycobiliproteins.

Table 4. Proteins and peptides from microalgae - pharmaceutical applications and supporting studies

Component	Pharmaceutical Potential	Supporting Studies and Findings
Microalgal proteins	Nutritional supplements, immune modulation, anti-inflammatory	*Arthrospira platensis* and *Chlorella vulgaris* contain 50-70% protein with balanced amino acids
Bioactive peptides	Antioxidant, antimicrobial, antiviral, anti-cancer	Enzymatic hydrolysis yields peptides that inhibit TNF-α, IL-6, and pathogens like *E. coli*
Extraction techniques	Enzymatic, mechanical, ultrasonication, pulsed electric field	Combined methods yield up to 80% protein extraction efficiency; key for preserving bioactivity
Species studied	*Chlorella*, *Scenedesmus*, *Nannochloropsis*, *Spirulina*	High protein content and digestibility; *Spirulina* shows 90% digestibility due to low cellulose
Pharma applications	Functional foods, cosmeceuticals, anti-hypersensitive agents	Peptides used in biofunctional foods and drug design for chronic inflammation and oxidative stress[1]

Carotenoids: Yellow to red-orange compounds with tetraterpenoid structures that support photosynthesis, especially prevalent in brown algae. Based on chemical composition, they are divided into:

Xanthophylls (oxygen-containing): e.g., fucoxanthin, astaxanthin, lutein, zeaxanthin

Carotenes (hydrocarbon-based): lack an O2 atom.

PBP: The water-solubilising non-toxic proteins are classified as phycoerythrins, phycocyanins, and allophycocyanins. PBPs can comprise up to sixty per cent of the soluble protein in Phycocyanin; for instance, it absorbs light in the 610-620 nm range and has documented therapeutic potential[41].

5.5 Lipids and Sterols

Lipid profiling studies in Brazilian seaweed species revealed glycolipids as the predominant lipid class (60-70%), followed by phospholipids (10-25%) and neutral lipids (10-15%). Rocha *et al.*[42] further confirmed that lipid content varies considerably with factors such as species type, seasonality, temperature, and geographic location. Table 5 provides the bioactive compounds of the marine algae and their supporting studies.

5.6 Pharmacological Properties of Marine Algae

With growing interest in leveraging natural bio compounds for disease treatment over conventional methods, the nutraceutical usage has significantly expanded, driven by the diverse biological activities of their bioactive constituents.

The pharmacological spectrum of marine algae is largely taxonomically driven. For instance, Rhodophyta species demonstrate strong antiviral and anticancer activities, Phaeophyta exhibit antioxidant and cardioprotective effects, Chlorophyta show metabolic and detoxifying potential, while Cyanophyta provide neuroprotective and antimicrobial actions. Such taxonomy-based differentiation supports targeted bio-prospecting and compound isolation. Figure 6 illustrates the potential role of marine algae-derived bioactive compounds as nutraceuticals in the prevention and treatment of various diseases through multiple biological mechanisms[42,43].

5.7 Antimicrobial and Antiviral Activities

Seaweed-derived compounds such as pigments, polyphenols and pigments have significant antiviral and antimicrobial properties. Diterpenes, terpenoids, Sesquiterpenoids has antimicrobial activities[44].

5.8 Anti-inflammatory Effects

Marine algal complexes have potential anti-inflammatory activities, in which fucoidans and sulphated polysaccharides are prominently recognised for their role in the modulation of inflammation[45].

5.9 Cardioprotective Potential

With the cardiovascular disease elevation, the marine algae compounds with ACE inhibitory properties have a prominent role[46]. Table 5 presents the information on the pharmacological characteristics of the marine algae[46].

6. Therapeutic Applications

6.1 Marine Algae in Drug Development and Marine Polysaccharides in Biomedical Applications

The sulphated polysaccharides like fucoidan, carrageenan and ulvan possess diversified biological

characteristics. Taxonomic clarity is important for the clinical translation of the algal metabolites. The species-specific variations in the polysaccharide structure, like fucoidans and carrageenan, directly impact the therapeutic effectiveness and bioavailability. So, integrating taxonomy with pharmacokinetics ensures the precise compound selection for the biomaterial and drug development. With the increasing scientific insights, the research is highly transitioning into real-world applications that aim to bridge the gap between laboratory discoveries and industrial implementations.

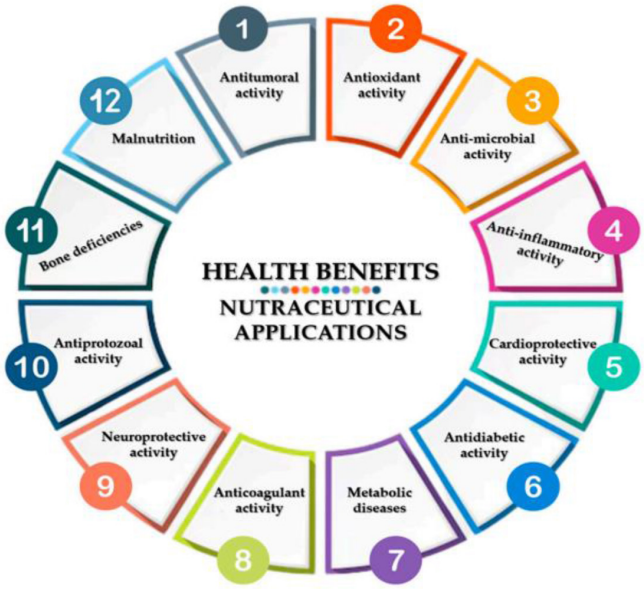


Figure 6. Treatment of the disease with nutraceuticals encompassing marine algae biological compounds.

6.2 Injectable and Stimuli-responsive Hydrogels

The injectable hydrogel is with more favour because of the minimally invasive administration and the adaptability for irregular tissue defects. Such in-situ forms the gels could be stimulated by stimuli such as pH and ionic strength. Temperature and pH for the creation of 3D cross-linked networks. Table 6 represents the comparative analysis of existing studies on polysaccharides and marine algae[47].

6.3 Nutraceutical and Functional Food Applications

Marine algae are ahead of extensive recognition for their contribution to health-improving foods and nutraceuticals due to the abundant nutrient content that includes essential amino acids, proteins, PUFAs, minerals, vitamins and pigments. Compounds such as agar, alginate and carrageenan are widely utilised in the food industry for their thickening, gelling and stabilising characteristics. In addition, the sulphated polysaccharides extracted from brown and red algae provide noticeable immunomodulatory, antioxidant and antiviral benefits. The pigments like fucoxanthin, chlorophyll, .astaxanthin serve as good noticeable sources of antioxidant and anti-obesity properties, which contribute to neurological and cardiovascular health. The microalgae like chlorella and spirulina are extensively available as high as the high protein supplements, whereas the plant and peptide sterols extracted from the algae play a vital role in the regulation of blood pressure and cholesterol levels[47].

Table 5. Pharmacological properties of marine algae - evidence from existing studies

Pharmacological property	Marine algae compounds involved	Supporting studies and findings
Antioxidant activity	Phlorotannins, carotenoids, polyphenols	Marine macroalgae exhibit strong antioxidant effects by scavenging free radicals[2]
Anti-inflammatory effects	Sulfated polysaccharides, terpenoids	Studies show inhibition of pro-inflammatory cytokines and enzymes like COX-23
Anticancer potential	Cryptophycin, kahalalide F, fucoidan	*In vitro* and *in vivo* studies demonstrate apoptosis induction and tumour suppression[2]
Antidiabetic properties	Fucoidan, ulvan, alginate	Algal extracts improve insulin sensitivity and reduce blood glucose levels in animal models
Cardioprotective effects	Polyunsaturated fatty acids, sulfated polysaccharides	Sargassum-derived compounds shown to reduce blood pressure and improve lipid profiles

Table 6. Comparative table: Marine algae and polysaccharides *vs*. existing studies[47]

Aspect	Marine algae in drug development	Existing studies	Marine polysaccharides in biomedical applications	Existing studies
Bioactive compounds	Phlorotannins, terpenoids, alkaloids, peptides	Studies highlight phlorotannins and terpenes as major contributors to antioxidant and anti-cancer effects	Fucoidan, alginate, carrageenan, chitosan	Fucoidan and alginate shown to inhibit cancer and inflammation; widely studied for drug delivery
Therapeutic potential	Anticancer, anti-inflammatory, antimicrobial	Cryptophycin and kahalalide F cited as potent anticancer agents from algae	Anticoagulant, immunomodulatory, wound healing	Fucoidan and chitosan used in tissue regeneration and stent coatings
Mechanism of action	ROS scavenging, enzyme inhibition, immune modulation	Algal metabolites shown to modulate cancer signalling pathways and oxidative stress	Scaffold formation, pH-responsive release, cell adhesion	Responsive to pH and temperature; used in smart drug delivery systems
Clinical relevance	Early-phase trials, nutraceuticals	Studies report preclinical success and potential for complementary cancer therapies	FDA-approved wound dressings, injectable hydrogels	Alginate and chitosan used in commercial biomedical products
Technological integration	Synthetic biology, metabolomics	Advances in omics and bioreactor systems enhance compound isolation	3D bio printing, electro spinning	Used in advanced tissue engineering and biosensor platforms
Challenges	Compound isolation, reproducibility	Studies note issues with bioavailability and standardisation	Long-term biosafety, extraction efficiency	Highlighted need for consistent extraction and characterisation methods
Environmental sustainability	Renewable, low ecological footprint	Emphasised as eco-friendly alternatives to synthetic drugs	Biodegradable, derived from marine waste	Supported as sustainable biomaterials with minimal toxicity[47]

6.4 Nano Formulation

Recent improvements in nano biotechnology have extended the usage of nanoformulations in the synthesis of drugs. Due to the complexities of outdated chemical and physical synthesis methods that include the production of toxic by-products, high energy demands and cost, there are increasing shifts towards eco-friendly and biological product development. Natural organisms such as algae, cyanobacteria, fungi and other higher plants prove to be highly valuable in green synthesis methods. Microalgae serve as reservoirs of several bioactive substance-like pigments and the enzymes which acts as reservoirs of several bioactive substance-like enzymes and pigments which act as natural formulations. But because of the solubility challenges, less than ten per cent of such bioactive molecules have transitioned into commercialised drug products. Still, the untapped potential makes them promising candidates in future development and delivery systems.

Nanoformulations function as a novel strategy in the development of cancer drugs and as a promising solution to the complexities associated with peptide-based drugs. The nanoplatforms improve the bioavailability of the drug, specificity and the overall therapeutic efficiency. Such applications in nanotheranostics provide new frontiers in medicine. The marine algae are rich sources of important nutraceuticals and are shaped by biological factors and environmental conditions[48,49]. The naturally derived compounds are specifically important for their neurodegeneration. The diverse range of natural substances attracted more interest

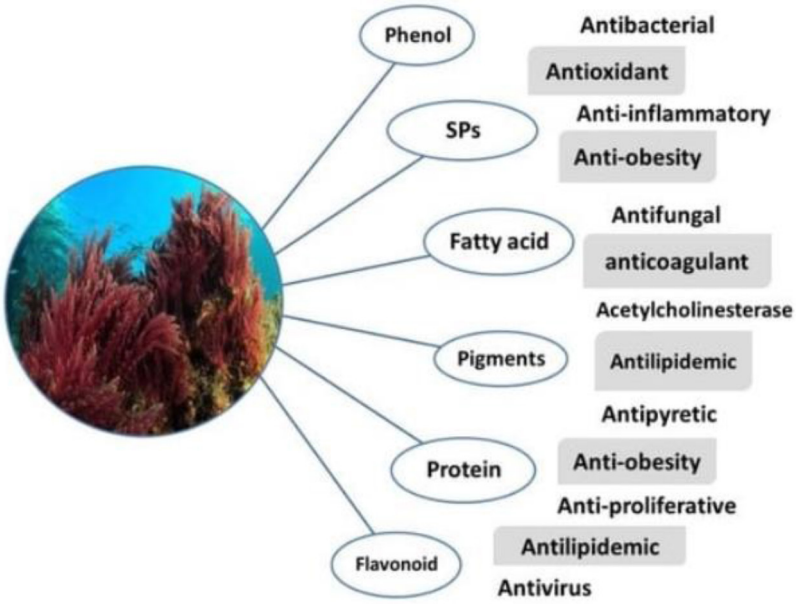


Figure 7. Pharmacological properties of red algae.

for their potential to alleviate symptoms and slow the progression of the neurological disorders that attention of both the pharmaceutical and academic sectors[50].

7. Challenges and Future Perspectives

Marine algae hold huge pharmaceutical potential but aspect barricades to commercialisation. Unpredictability in chemical configuration due to environment, species, and harvest timing complicates reproducibility, while largescale cultivation requires costly infrastructure, energy, and water[51]. Postharvest processing and drying, separation, and purification have practical and monetary challenges. Regulatory frameworks remain unpredictable, decelerating drug endorsements, and safety concerns like heavy metal contamination demand strict quality control[52]. Sustainable aquaculture, seasonal harvesting, and ecofriendly methods are vital to protect biodiversity. Biotechnology, including genetic engineering, synthetic biology, and CRISPR, enhances yields and enables production of therapeutic proteins[53]. Figure 7 shows the Pharmacological properties of red algae[54].

Omics technologies accelerate drug candidate identification, while nanotechnology improves stability and targeted delivery. Addressing technical, regulatory, and ecological challenges is essential to unlock algae's full potential in pharmaceuticals[55].

8. Future Directions in Marine Algae-based Therapeutics

The marine algae in therapeutic development have been observed to be shaped by the rapid advancement in biotechnology and the growing emphasis on sustaining the future. The innovations in metabolomics, genomics and other omics technologies are enabling researchers to decode complex metabolic pathways with significant medical potentialities. In addition, the improvement in the cultivation of algal biomass makes it more efficient[56]. Clinical research is expanding with human trials for validating the effectiveness and safety of marine algae-derived compounds.

9. Conclusion

Seaweeds are nutrient-rich resources that are increasingly valued for their nutraceutical and pharmaceutical potential. They provide bioactive compounds with antioxidant, antitumor, anti-inflammatory, antimicrobial and neuroprotective properties, which support the prevention and management of metabolic disorders, Alzheimer's disease and other health conditions. The research highlighted the classification, extraction techniques and metabolomic profiles of seaweed-derived bioactive compounds, while the sustainable extraction technologies aim to enhance

the purity and yield. However, the challenges include contamination risks and limited consumer acceptance. Future research should focus on advanced extraction techniques, the integration of seaweed bioactive compounds into functional foods, the application of marine biotechnology to enhance compound stability and bioavailability and the conservation of marine ecosystems to ensure sustainable utilisation. Overall, the seaweeds remain an underutilised marine resource with significant potential for nutrition, human health and drug discovery.

10. References

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Author Contribution

A. Umadevi: conceptualised the review and conducted the literature search and drafted the initial manuscript. Malarkodi Velraj: critically revised the manuscript for important intellectual content and supervised the work. Both authors approved the final version of the manuscript.