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Pharmaceutical Treasures of the Sea: Marine Plants in Anti-Inflammatory and Neuroprotective Therapies

Abdol Ghaffar Ebadi[1]*, Mehran Moslemi[1] and Zeliha Selamoglu[2-4]

[1]*Department of Agriculture, Jo.C, Islamic Azad University, Iran*

[2]*Department of Medical Biology, Medicine Faculty, Nigde Omer Halisdemir University, Turkey*

[3]*Western Caspian University, Azerbaijan*

[4]*Khoja Akhmet Yassawi International Kazakh-Turkish University, Faculty of Sciences, Department of Biology, Kazakhstan*

***Corresponding author:** Abdol Ghaffar Ebadi, Department of Agriculture, Jo.C, Islamic Azad University, Jouybar, Iran

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ABSTRACT

Marine plants are a comparatively untapped reservoir of bioactive compounds with promise for application in the treatment of chronic inflammatory and neurodegenerative diseases. Unlike plants on land, marine plants are adapted to saline, oxidative, and UV-rich conditions, leading to the evolution of structurally sophisticated and biologically active molecules. Polysaccharides, polyphenols, phlorotannins, and sterols from marine animals such as Ecklonia cava, Zostera marina, and Avicennia marina have been found to have potent anti-inflammatory and neuroprotective properties. They modulate key signaling pathways such as NF-κB, MAPK, and PI3K/Akt and thereby inhibit the release of pro-inflammatory cytokines and oxidative neuronal damage. Preclinical studies show that these marine-derived molecules can protect against diseases such as Alzheimer's disease, Parkinson's disease, and multiple sclerosis, and reduce systemic inflammation in metabolic diseases. Despite promising pharmacological profiles, limitations such as low bioavailability and lack of clinical validation remain. This mini-review recapitulates the recent advances in marine plant-derived compounds with anti-inflammatory and neuroprotective properties, outlining their mechanisms of action, therapeutic potentials, and future perspectives. The integration of marine pharmacognosy and modern drug development strategies could pave the way for novel, safe, and efficacious therapeutics for some of the most incapacitating health conditions of our time.

Keywords: Marine Pharmacognosy; Anti-Inflammatory Agents; Neuroprotection; Seaweed Extracts, Natural Therapeutics

Introduction

Marine algae such as macroalgae (seaweeds), seagrasses, and mangroves are a diverse source of structurally diverse bioactive compounds. These species inhabit dynamic coastal ecosystems with intense salinity, high ultraviolet (UV) radiation, mechanical stress, and fluctuating temperatures. Marine algae have evolved sophisticated metabolic pathways in response to such stressful conditions, producing secondary metabolites with potent pharmacological activities. Remarkably, the bioactives exhibit antioxidant, anti-inflammatory, antimicrobial, and neuroprotective activities [1-7]. In the past several decades, inflammatory and neurodegenerative disorders such as rheumatoid arthritis, Alzheimer's disease, and Parkinson's disease have experienced explosive growth. Disadvantages of available therapeutic medications—e.g., side effects, cost, and resistance—have prompted efforts to seek out alternative treatments. Marine-derived products offer promising drug candidates since they demonstrate novel modes of action and are biocompatible [8-10]. The neuroprotective and anti-inflammatory potential of marine plants, based on both in vivo and in vitro evidence, is thus receiving growing scientific attention (Table 1).

Table 1: Representative Marine Plant Species and Their Pharmacological Activities.

Species	Active Compounds	Therapeutic Action	Target Pathway	References
Ecklonia cava	Phlorotannins	Neuroprotection, Anti-inflammatory	NF-κB, MAPK	[5]
Avicennia marina	Flavonoids, Sterols	Anti-inflammatory	COX-2, iNOS	[6]
Zostera marina	Phenolic acids	Antioxidant, Neuroprotective	PI3K/Akt	[7]

Bioactive Compounds in Marine Plants

Polysaccharides

Sulfated polysaccharides such as fucoidan, alginate, carrageenan, and laminarin-mainly from brown algae (Phaeophyceae) have been found to possess different bioactivities. Fucoidan, for instance, controls immunity by inhibiting pro-inflammatory cytokines like IL-6 and TNF-α and inducing macrophage phagocytosis. Such polysaccharides are structurally heterogeneous depending upon species, season, and habitat and affect potency and specificity [11].

Polyphenols and Phlorotannins

Polyphenols, especially phlorotannins from brown algae such as Ecklonia cava, have significant antioxidant and anti-inflammatory activities. Phlorotannins act as free radicals scavengers (reactive oxygen species, ROS), inhibit nuclear factor-kappa B (NF-κB), and modulate mitogen-activated protein kinase (MAPK) signaling. Experiments showed that these compounds can inhibit cyclooxygenase-2 (COX-2) and inhibit nitric oxide production in lipopolysaccharide-stimulated macrophages [12,13].

Sterols and Terpenes

Marine sterols like fucosterol and terpenes like squalene, derived from seaweeds and mangroves, exhibit antioxidative and anti-inflammatory effects. Fucosterol inhibits the expression of IL-1β, IL-6, and COX-2 and regulates PI3K/Akt pathways for cell survival and immune response. These molecules also decrease oxidative damage by enhancing endogenous antioxidant enzyme activity based on Table 2 [14].

Table 2: Bioactive Compounds from Marine Plants: Types, Mechanisms, and Therapeutic Potentials.

Compound Group	Example Compounds	Marine Source	Bioactivity Mechanism	Therapeutic Relevance	References
Polysaccharides	Fucoidan, Alginate, Carrageenan, Laminarin	Brown algae (*Fucus, Laminaria, Undaria*)	Inhibits IL-6 and TNF-α; promotes phagocytosis; modulates complement activation	Anti-inflammatory, Immunomodulatory	[5-7]
	Fucoidan	*Fucus vesiculosus, Ecklonia cava*	Suppresses cytokine storm, modulates macrophage and dendritic cell activation	Autoimmune disease management, anti-cancer	[12, 13]
Polyphenols & Phlorotannins	Phloroglucinol, Dieckol, Eckol	*Ecklonia cava, Ascophyllum nodosum*	Scavenges ROS; inhibits NF-κB, COX-2, and iNOS; downregulates MAPK and inflammatory enzymes	Neuroprotective, Anti-inflammatory	[10-12]
	Phlorotannins	Brown algae (*Eisenia bicyclis*)	Inhibits NO production in LPS-stimulated macrophages; reduces oxidative stress and lipid peroxidation	Atherosclerosis prevention, anti-aging	[8]
Sterols & Terpenes	Fucosterol	*Sargassum fusiforme, Turbinaria*	Inhibits COX-2, IL-1β, IL-6; activates PI3K/Akt for cell survival	Antioxidant, Anti-neuroinflammatory	[14]
	Squalene	Mangroves, deep-sea algae	Enhances SOD, catalase, and GPx enzyme activity; reduces ROS damage	Skin health, Cardioprotection, Brain aging	[6,10]

Anti-Inflammatory Mechanisms of Marine Plant Compounds

Marine compounds target several molecular pathways associated with inflammation. The major mechanisms include inhibition of NF-κB and MAPK pathways, COX-2 enzyme expression inhibition, and reduction in the secretion of pro-inflammatory cytokines such as IL-1β, IL-6, and TNF-α. For example, extracts from Zostera marina and Avicennia marina are effective in inhibiting NF-κB activation and cytokine secretion in macrophage cell models. The extracts also reduce intracellular ROS, inhibiting oxidative stress-mediated inflammation according to Table 3 [5,9,13].

Table 3: Anti-Inflammatory Potential of Marine Plant Extracts (% Inhibition of IL-6 Production).

Extract Source	Cell Line Used	IL-6 Inhibition (%)	Reference
Ecklonia cava	RAW 264.7	65	[5]
Zostera marina	THP-1	58	[9]
Avicennia marina	RAW 264.7	70	[10]
Gracilaria sp.	THP-1	60	[7]

Neuroprotective Actions and Therapeutic Targets

Marine plant metabolites exhibit neuroprotection through diverse mechanisms, including ROS scavenging, mitochondrial protection, and modulation of key signaling pathways like PI3K/Akt and Nrf2. Phlorotannins from Ecklonia cava and sulfated polysaccharides from red algae were shown to suppress apoptosis in neuronal cells in Alzheimer's and Parkinson's disease models (Tables 4 & 5). These metabolites also improve cognitive functions by suppressing β-amyloid aggregation and neuroinflammation [10,11,14].

Table 4: Neuroprotective Effects of Marine-Derived Compounds (% Reduction in ROS Production).

Marine Compound	Neuronal Model	ROS Reduction (%)	Reference
Phlorotannins (*E. cava*)	SH-SY5Y	60	[11]
Sulfated polysaccharides	APP/PS1 mice	45	[12]
Fucosterol	BV-2	53	[13]
Halophilic polyphenols	SH-SY5Y	50	[14]

Table 5: Signaling Pathway Modulation by Marine Plant Extracts (% Change from Control).

Extract Source	NF-κB Inhibition (%)	MAPK Inhibition (%)	PI3K/Akt Activation (%)	Reference
Ecklonia cava	70	55	40	[5]
Zostera marina	60	52	45	[9]
Avicennia marina	75	58	38	[6]
Sargassum muticum	62	50	43	[8]

Challenges and Limitations

Despite their auspicious pharmacological activities, drugs from marine plants are also plagued with some translational issues. These include low oral bioavailability, rapid metabolism rates, and undesirable pharmacokinetic profiles. In addition, geographical and season factors influence metabolite content, rendering standardization problematic. The lack of clinical trials is also a limiting factor to regulatory approval and therapeutic applications. All of these are to be overcome with good analytical devices and scale-up extraction protocols [6,8].

Future Perspectives

In order to achieve complete therapeutic potential of seaweed compounds, future research should give high priority to nanoformulation techniques, synthetic analog design, and systems biology tools. Nanoencapsulation will likely enhance bioavailability and specificity of targeting, while synthetic analogs would be able to improve stability and efficacy. Integration of omics-based tools will also enable better understanding of bioactive mechanisms. Furthermore, sustainable harvesting and aquaculture practices should be adopted to save the environment and deliver resources [7,12-14].

Conclusion

Marine algae are a rich, untapped source of highly bioactive molecules of high anti-inflammatory and neuroprotective potential. Their mechanisms of action encompass a range of biological pathways and offer promising therapeutic options to current treatments for chronic inflammatory and neurodegenerative diseases. Despite ongoing challenges, ongoing research and technical development hold promise for translation of therapeutics from marine-derived products to clinically effective medicines.

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Abdol Ghaffar Ebadi. Biomed J Sci & Tech Res

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