

Marine Algae: A rich reservoir of bioactive compounds with nutritional and therapeutic potential

Preeti George * and Suganya W

Department. Of Botany, Government Arts College, Coimbatore-641018, Tamil Nadu, India.

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Abstract

Marine algae represent an abundant and renewable biological resource with growing relevance in the fields of health and biomedicine due to their capacity to produce structurally diverse bioactive compounds. Both microalgae and macroalgae, including representatives of the red (Rhodophyta), green (Chlorophyta), and brown (Phaeophyta) algal groups, generate metabolites that support their ecological survival while also exhibiting notable pharmacological properties. This review consolidates current research findings across four major categories of biological activity: anti-inflammatory, antioxidant, anti-obesity, and anticoagulant effects. Polysaccharides such as fucoidans isolated from brown algae (e.g., *Undaria pinnatifida* and *Macrocystis pyrifera*), along with extracts derived from red algae (*Kappaphycus alvarezii*) and green algae (*Ulva pertusa*), have demonstrated significant immunomodulatory and enzyme-inhibitory activities. In addition, marine algae are important sources of antioxidant molecules, including polyphenols, carotenoids, and sulfated polysaccharides, identified in species such as *Callophyllis japonica*, *Gracilaria tenuistipitata*, *Ulva lactuca*, and *Ulva reticulata*. Certain algal metabolites—such as fucoxanthin, siphonoxanthin, and phlorotannin—exert anti-obesity effects through multiple metabolic pathways, while sulfated galactans and fucans provide promising alternatives to conventional anticoagulants. Beyond their bioactive potential, marine algae also offer a comprehensive nutritional profile, reinforcing their value as functional foods and as sources of biomedical compounds.

Keywords: Macroalgae; Bioactive Compounds; Seaweeds; Anti-Inflammatory; Antioxidant; Anti-Obesity; Anticoagulant; Nutrients; Functional Food

1. Introduction

Marine macroalgae, commonly referred to as seaweeds, are multicellular photosynthetic organisms traditionally categorized into three principal groups—Rhodophyta, Chlorophyta, and Phaeophyceae—based on their pigment composition. These organisms occupy diverse marine habitats and play a fundamental ecological role, exhibiting morphological variation ranging from simple filamentous structures to complex kelp forests [1].

With an estimated hundreds of thousands of documented species, marine algae constitute a vast and underexplored source of chemically diverse secondary metabolites. This extensive biodiversity enhances their potential as reservoirs of novel compounds with therapeutic relevance [2]. Historically consumed for their high nutritional value, seaweeds are now increasingly investigated for their bioactive constituents, including polyphenols, peptides, lipids, and polysaccharides, which exhibit antioxidant, anti-inflammatory, antihypertensive, and other health-promoting properties [3]. As a result, marine-derived metabolites have gained attention as promising candidates for pharmaceutical, nutraceutical, and functional food applications [4].

* Corresponding author: Preeti George.

1.1. Anti-inflammatory Activity

Inflammation is a complex physiological process initiated by immune cells in response to infections, chemical agents, physical injury, or metabolic imbalance. While acute inflammation is a protective response, its persistence can contribute to tissue damage and the development of chronic disorders affecting organs such as the liver, brain, heart, and lungs [5].

Among algal metabolites, fucoidans—sulfated polysaccharides predominantly found in brown macroalgae—have attracted significant attention due to their antiproliferative, antioxidant, and anti-tumor properties [6]. Species such as *Undaria pinnatifida* and *Macrocystis pyrifera* are particularly rich in fucoidans that demonstrate strong anti-inflammatory activity through modulation of immune signaling pathways [7]. Similarly, extracts obtained from the red alga *Kappaphycus alvarezii* have shown marked inhibition of hyaluronidase, an enzyme closely associated with inflammatory progression. This activity is attributed to a combination of secondary metabolites, including flavonoids, alkaloids, terpenoids, and amino acids [8].

Additional studies highlight the anti-inflammatory efficacy of brown algae such as *Ecklonia cava* and *Ascophyllum nodosum*, which are rich in polyphenolic compounds capable of attenuating inflammatory responses [9,10]. Furthermore, extracts from the green alga *Ulva pertusa* have been shown to alleviate abdominal pain linked to colon inflammation, suggesting a role in suppressing prolonged immune activation [11].

1.2. Antioxidant Properties

Oxidative reactions involving reactive oxygen species can damage cellular components such as lipids, proteins, and nucleic acids, ultimately leading to tissue dysfunction. Antioxidants counteract these effects by neutralizing free radicals or inhibiting oxidative chain reactions [12].

Marine algae synthesize a wide range of antioxidant compounds, including polyphenols, carotenoids, vitamins, minerals, and sulfated polysaccharides, many of which occur at higher levels than in terrestrial plants [13]. For instance, ethanol extracts of the red alga *Callophyllis japonica* have demonstrated strong antioxidant activity [14]. Similarly, phytochemical analyses of *Ulva lactuca* reveal a high concentration of flavonoids, which correlate with effective free-radical scavenging capacity [15]. In vivo studies further indicate that hot-water extracts of *Ulva reticulata* reduce oxidative stress markers in hepatic tissue, highlighting their protective antioxidant potential [16].

Marine macroalgae also possess unique sulfated polysaccharides within their cell walls, such as fucoidan, ulvan, and carrageenan, which differ structurally from those found in terrestrial plants. These compounds have been associated with reduced oxidative damage and may play a role in mitigating chronic inflammation, cardiovascular disease, and age-related disorders [17]. Notably, sulfated polysaccharides isolated from *Gracilaria caudata* have exhibited pronounced antioxidant activity, reinforcing the value of macroalgae as sources of natural antioxidant agents [18].

1.3. Anti-obesity Effects

Several bioactive compounds derived from marine algae exhibit anti-obesity potential by influencing lipid metabolism, adipocyte differentiation, and energy expenditure. Among these, fucoxanthin and sulfated polysaccharides have been shown to suppress fat accumulation, enhance thermogenesis, and limit dietary lipid absorption [19].

Fucoxanthin, a carotenoid abundant in edible brown seaweeds, has demonstrated beneficial effects on body weight regulation and lipid metabolism in experimental models [20]. Another carotenoid, siphonoxanthin—isolated from green algae such as *Caulerpa lentillifera*—has been reported to inhibit adipocyte differentiation in 3T3-L1 cells by regulating genes involved in lipid synthesis and storage [21].

Phlorotannins, a class of polyphenols unique to brown seaweeds, function as natural inhibitors of pancreatic lipase, thereby reducing fat digestion and absorption. *Ecklonia cava* is recognized as one of the richest sources of these compounds [22]. Additionally, alginates, which form the structural matrix of brown algae, contribute to satiety and reduced caloric intake; species such as *Durvillaea potatorum* and *Macrocystis pyrifera* are notable for their high alginate content [23]. Recent cellular studies indicate that extracts from *Sargassum horneri* and *Ulva australis* downregulate genes associated with lipid storage, resulting in decreased fat accumulation and supporting their potential as natural anti-obesity supplements [24].

1.4. Anticoagulant Activity

Thrombosis involves the formation of blood clots within blood vessels and poses serious health risks when clots obstruct critical circulatory pathways. Although heparin remains a widely used anticoagulant, its clinical application is limited by adverse effects such as bleeding complications and thrombocytopenia [25].

Marine algae have emerged as alternative sources of anticoagulant compounds, particularly sulfated polysaccharides that exhibit heparin-like activity [26]. Polysaccharides isolated from species of the genus *Monostroma* have been reported to inhibit thrombin more effectively than heparin in vitro. Likewise, a sulfated galactan extracted from the green alga *Codium divaricatum* enhances thrombin neutralization through activation of heparin cofactor II [27].

Further evidence of anticoagulant potential has been observed in sulfated polysaccharides derived from *Padina tetrastrum* and *Ulva fasciata*, which prolong clotting time by targeting components of the intrinsic coagulation pathway [28]. These findings highlight marine algae as promising sources of safer, naturally derived anticoagulant agents.

Table 1 A review of bioactive properties of different macroalgae species

Property	Key Mechanism	Macroalgae Species	Bioactive Compounds
Anti-inflammatory	Inhibits inflammatory reactions and hyaluronidase enzyme activity	<i>Undaria pinnatifida</i> <i>Kappaphycus alvarezii</i> <i>Ecklonia cava</i>	Fucoidans Flavonoids Alkaloids Polyphenolic compounds
Antioxidant	Stops the oxidation process by hindering free radical reactions, protecting against tissue injury.	<i>Ulva lactuca</i> <i>Gracilaria caudata</i>	Flavonoids Sulfated polysaccharides
Anti-obesity	Inhibits fat absorption, increases energy expenditure, promotes satiety, suppresses fat cell development.	<i>Undaria pinnatifida</i> <i>Kappaphycus alvarezii</i> <i>Ecklonia cava</i>	Fucoidans Flavonoids Alkaloids Polyphenolic compounds
Anticoagulant	Prevents the formation of blood clots (thrombosis) by potentiating thrombin inhibition.	<i>Ulva fasciata</i> <i>Codium divaricatum</i>	Sulfated polysaccharides Sulfated galactans

1.5. Vitamins and Minerals

Edible marine macroalgae are increasingly recognized as sustainable food resources with exceptional nutritional value. In addition to supplying a broad spectrum of vitamins—including water-soluble B vitamins and fat-soluble vitamins A, D, and E—macroalgae contain a diverse range of bioactive constituents such as polyphenols, sterols, and photosynthetic pigments, notably fucoxanthin and astaxanthin. Their mineral profile is particularly noteworthy, with substantial levels of iodine, selenium, and magnesium [29].

The nutritional composition varies considerably among species. Species such as *Porphyra umbilicalis*, *Ulva lactuca*, and *Gracilaria vermiculophylla* are especially rich in antioxidant vitamins, including vitamins C and E, as well as trace elements such as selenium, magnesium, and zinc. Remarkably high concentrations of vitamin C have been reported in the green alga *Ulva flexuosa* and the red alga *Eucheuma denticulatum* [30]. Although vitamin B12 is predominantly animal-based, red algae such as *Palmaria palmata* and *Porphyra tenera* provide a plant-associated source [31].

2. Conclusion

Marine algae serve as a prolific reservoir of bioactive metabolites which exhibit significant therapeutic potential as anti-inflammatory, antioxidant, anti-obesity, and anticoagulant agents. This review highlights how these structurally diverse

compounds modulate critical biological pathways—such as inhibiting inflammatory enzymes, neutralizing free radicals, and regulating lipid metabolism—while simultaneously providing a robust profile of essential vitamins and minerals. As the global demand for sustainable and natural pharmaceuticals rises, these marine-derived compounds offer a viable, renewable alternative to synthetic drugs with fewer associated side effects. This study directly benefits society by identifying sustainable pathways for creating algae-based nutraceuticals to treat chronic illness, suggesting that future efforts should prioritize large-scale clinical trials and optimized extraction methods to harness the full therapeutic power of marine metabolites.

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