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ORIGINAL RESEARCH

A Comprehensive Review on Marine-Derived Antioxidants: Sources, Mechanisms, and Applications

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Abstract

This review explores the antioxidant activity of marine-derived compounds, with a focus on marine biota and polysaccharides. The marine environment, which covers over 70% of Earth's surface, is a largely untapped source of bioactive compounds with unique structures and potent antioxidant properties. Marine organisms, including seaweeds, sponges, and microorganisms, produce a variety of bioactive molecules, such as phenolic compounds, polysaccharides, terpenoids, and peptides, which demonstrate significant antioxidant activity. These compounds help mitigate oxidative stress, a key factor in numerous diseases such as cancer, cardiovascular disorders, neurodegenerative diseases, and aging. The review highlights the diverse antioxidant mechanisms of marine sources, including radical scavenging, metal chelation, and the enhancement of endogenous antioxidant defenses. Notably, marine-derived polysaccharides, such as fucoidans from brown algae, exhibit multi-faceted antioxidant effects, contributing to their therapeutic potential. The antioxidant capabilities of marine microorganisms, including microalgae, bacteria, and fungi, are also discussed, showcasing their contribution to marine biotechnological applications. Furthermore, the paper examines the growing applications of marine antioxidants across industries such as food preservation, pharmaceuticals, cosmetics, and nutraceuticals. With advancements in extraction technologies and sustainable cultivation methods, marine antioxidants hold great promise for addressing oxidative stress-related health issues. This review underscores the importance of further research into the bioactive compounds from marine sources for future therapeutic, cosmetic, and food applications, offering valuable insights for the development of novel antioxidants to improve human health and well-being.

Keywords: Antioxidants; Marine Biota; Marine Sponge; Polysaccharides Activity; Antioxidant Mechanism; Bioactive Metabolites; Sustainable Production.

1 | INTRODUCTION

In recent decades, the marine environment has proven to be the richest source of bioactive compounds with diverse applications in the pharmaceutical, nutraceutical, and cosmeceutical industries [1]. Among the bioactive properties, antioxidant properties have gained the most attention due to their potential to prevent and treat various oxidative stress-related diseases [2]. The marine environment, covering approximately 70% of the Earth's surface, represents an untapped reservoir of novel bioactive compounds [3]. Marine organisms have evolved unique biochemical and physiological mechanisms due to their habitats, such as high salinity, high pressure, low temperature, and limited nutrients. This adaptation has led to the production of structurally diverse and biologically active compounds, including phenolic compounds, peptides, terpenoids, carotenoids, and polysaccharides, many of which show antioxidant potential [4]. From the diverse marine organisms, seaweeds, sponges, and marine microorganisms (bacteria, fungi, and microalgae) have emerged as great sources of antioxidant compounds [5]. Marine organisms and their associated microorganisms synthesize phenolic compounds, terpenes, and other secondary metabolites with potent free radical scavenging capabilities. Marine microorganisms, including bacteria and fungi, produce unique antioxidant compounds that often differ structurally from those found in their terrestrial counterparts [6]. Polysaccharides derived from marine organisms have also drawn attention due to their diverse structures, relatively high safety profiles, and bioactivities. Marine-derived polysaccharides not only exhibit antioxidant activity but also indirectly enhance the body's endogenous antioxidant defenses by providing signals to pathways involved in oxidative stress responses and modulating gene expression [7]. Various structural parameters, such as monosaccharide composition, molecular weight, and three-dimensional conformation, have an impact on the antioxidant efficacy of these polysaccharides [8]. Marine sponges possess biological functions such as cytotoxicity, antibacterial activity, thrombolytic properties, antioxidant effects, antiviral capabilities, and antifungal action. All of these functions pertain to its antioxidant capacity. Antioxidants are essential for human health to safeguard cells from free radical damage. Specific beneficial molecules, termed secondary metabolites, are designated as phytochemicals in the scientific literature. Phytochemically active compounds have been demonstrated to enhance the maintenance of internal systems by optimizing metabolism and regulating hormones. They aid in safeguarding us from environmental pollutants. Numerous bioactive compounds have distinctive biological features and may hold potential therapeutic benefits [9]. Marine sponges' secondary metabolite pathways make them good pharmacological study subjects for low-treat ailments. The medical world uses marine sponge secondary metabolites. Because of their unique secondary metabolite pathways, marine sponges provide good pharmacological study subjects for disorders with few therapeutic options. Marine sponge secondary metabolites are used in modern medicine. In just five years, sponge-associated bacteria found 140 new compounds. Bioactive sponges with antibacterial, antiviral, antifungal, nematicidal, immunosuppressive, muscle relaxant, and antiinflammatory properties. Anti-inflammatory, anticancer, and antibacterial medicines generated from sponges are being investigated [10]. This review paper aims to provide an overview of the antioxidant activity of marine biota and polysaccharides derived from marine organisms. We have explored the various sources of antioxidants in marine organisms with a particular focus on seaweeds, sponges, and their associated microorganisms. Here, the chemical composition of marine biota, their structural characteristics, and their mechanisms have been discussed, with special emphasis on polysaccharides. Furthermore, we have discussed the factors that affect the antioxidant activity of marine-derived polysaccharides and their potential applications in pharmaceutical, cosmetic, and food industries. By analyzing the current knowledge in this field, this review paper intends to provide valuable insights for future research and development of marine-derived antioxidants for human health and well-being.

2 | ANTIOXIDANT AND OXIDATION MECHANISMS

The production of reactive oxygen species (ROS) in biological systems and the capacity of these systems to detoxify them or repair the resultant damage are the two components of oxidative stress [11]. In order to address the potential advantages of marine-derived antioxidant compounds, it is essential to comprehend the mechanisms of oxidation and antioxidant activity.

2.1 | Oxidation processes

Chemical reactions involving the transfer of electrons from one oxidation state to another occur in oxidation reactions. Metabolic activities involving oxidation are fundamental to all living systems, but especially to the mitochondrial electron transport chain, which is responsible for generating energy. Oxygen is the last electron acceptor in aerobic respiration, which results in ATP generation. On the other hand, some inefficiencies in this process cause ROS to be formed, specifically, an early and incomplete reduction of about 1-3% of oxygen molecules [12]. Reactive oxygen species (ROS) comprise a range of free radicals and reactive compounds originating from molecular oxygen. The principal reactive oxygen species generated in biological systems comprise: superoxide anion (O_2•$^-$), hydrogen peroxide (H_2O_2), hydroxyl radical (•OH), peroxyl radicals (ROO•), singlet oxygen ($^1O_2$), and nitric oxide (NO•), among others. Reactive oxygen species are essential for homeostasis, cellular signaling, and immunological function under normal physiological settings. When reactive oxygen species generation surpasses the cellular capacity for antioxidant defenses, oxidative stress results in damage to cellular components [13]. The detrimental consequences of an inordinate amount of reactive oxygen species (ROS) include the oxidation of carbohydrates, lipid peroxidation, protein oxidation, and DNA damage. Numerical diseases, such as cancer, diabetes, cardiovascular diseases, neurodegenerative disorders, and aging-related conditions, are the consequence of chronic oxidative stress. This emphasizes the significance of preserving redox homeostasis by implementing appropriate antioxidant defenses [14].

2.2 | Antioxidant mechanisms

Antioxidants are compounds that can inhibit or avert the oxidation of susceptible substrates, even in minimal doses. Their primary function is to protect biological systems against oxidative damage by inhibiting the generation of reactive oxygen species (ROS), neutralizing them after formation, or repairing the molecular damage they induce [15]. Having a very complex antioxidant defense system is important for the body because oxidative stress is a key part of many illnesses and the aging process. There are two main types of antioxidants in this system: endogenous antioxidants are made by the body itself, and foreign antioxidants come from food and other outside sources (Table 1 and Table 2). The balance of redox states and the integrity of cells are maintained by these defense systems working together [16].

Table 1. Endogenous antioxidant mechanism.

Category	AO	Function / Mechanism
Enzymatic	SOD	Catalyzes the dismutation of superoxide into oxygen and hydrogen peroxide.
	CT	Converts hydrogen peroxide into water and oxygen.
	GPx	Reduces hydrogen peroxide and lipid hydroperoxides using glutathione.
	TD	Maintains proteins in a reduced state; involved in redox signaling.
Non-Enzymatic	GT	Major cellular antioxidant; scavenges ROS; GPx substrate.
	UA	Scavenges hydroxyl radicals and singlet oxygen.
	CE	Electron transport chain component; lipid-soluble antioxidant.
	MT	Potent free radical scavenger; crosses membranes and the blood-brain barrier.
	LA	Regenerates other antioxidants and chelates metal ions.

[AO = Antioxidant, SOD = Superoxide dismutase, CT = Catalase, GPx = Glutathione peroxidase, GR = Glutathione reductase, TD = Thioredoxin, GT = Glutathione, UA = Uric acid, CE = Coenzyme, MT = Melatonin, LA = Lipoic acid].

However, non-enzymatic antioxidants function as either direct scavengers of free radicals or as cofactors for enzymatic systems. Glutathione (GT), a tripeptide that is present in the majority of cells, is a significant cellular antioxidant that directly scavenges ROS and serves as a substrate for GPx [22]. Uric acid (UA), an additional critical endogenous molecule, plays a substantial role in the antioxidant capacity of the plasma by neutralizing hydroxyl radicals and singlet oxygen [23]. In the electron transport chain, the lipid-soluble molecule coenzyme Q10 serves as an antioxidant that stabilizes membranes and produces energy [24]. Comparably, the neurohormone melatonin, which is released by the pineal gland, functions as a strong scavenger of free radicals and may penetrate cell membranes and the blood-brain barrier to protect a variety of tissues, including the brain [25]. Through the chelation of pro-oxidant metal ions and the regeneration of other antioxidants, including vitamins C and E, lipoic acid provides an additional line of protection [26]. An effective internal defense against oxidative damage is offered by this blend of enzymatic and non-enzymatic antioxidants.

2.3 | Endogenous antioxidant systems

Endogenous defensive mechanisms, although essential, are not always adequate in the presence of severe oxidative stress. The body relies heavily on exogenous antioxidants to supplement these systems, which are mostly supplied through diet. Vitamin C (ascorbic acid) is a water-soluble antioxidant that is necessary for the production of dietary antioxidants. It efficiently scavenges reactive oxygen species (ROS) and regenerates oxidized vitamin E, extending its action. Tocopherols and tocotrienols are components of vitamin E, a lipid-soluble antioxidant that integrates into cell membranes to protect them against lipid peroxidation [27]. Antioxidative chain reactions can't happen because carotenoids, such as β-carotene and lycopene, get rid of peroxyl radicals and singlet oxygen [28]. Also, polyphenols, which are a group of substances found in plants and include phenolic acids and flavonoids, work as antioxidants in several ways, such as by changing the way enzymes work, binding to metals, and removing free radicals [29]. Altogether, these food antioxidants provide a full defense against oxidative stress, often working with the body's own defenses.

Table 2. Exogenous antioxidant mechanism.

Category	Antioxidant	Function / Mechanism
Dietary	Vitamin C	Water-soluble; scavenges ROS; regenerates vitamin E.
	Vitamin E	Lipid-soluble; protects cell membranes from lipid peroxidation.
	Carotenoids	Quench singlet oxygen; scavenge peroxyl radicals.
	Polyphenols	ROS scavenging, metal chelation, and enzyme modulation.
Marine-derived	Polysaccharides	From seaweeds, marine microbes, and invertebrates, diverse antioxidant mechanisms exist.
	Phlorotannins	Polyphenols in brown algae: potent ROS scavengers.
	Mycosporine	UV-absorbing marine compounds; antioxidant activity.
	Carotenoids	From marine microalgae/invertebrates, strong singlet oxygen quenching.
	Terpenes	From marine sponges and microbes, diverse antioxidant mechanisms.

Due to the unique structural features of marine bioactive compounds, marine-derived antioxidants have become an exciting new area of antioxidant study. Toxic qualities of polysaccharides found in seaweed, marine microorganisms, and invertebrates include metal chelation and ROS removal. In brown algae, phenolic chemicals called phlorotannins have strong ROS-scavenging abilities and other bioactivities that are good for your health. Mycosporine-like amino acids, UV-absorbing chemicals produced by marine organisms, offer photoprotection and exhibit antioxidant capabilities [30]. Marine carotenoids, sourced from microalgae and invertebrates, are effective singlet oxygen quenchers and have garnered interest for their potential in mitigating oxidative stress-related illnesses [31]. Finally, terpenes derived from marine sponges and their symbiotic microbes exhibit a diverse range of antioxidant processes, hence enhancing the therapeutic potential of marine natural products [32]. Overall, antioxidants are critical for preserving redox equilibrium and shielding the organism from oxidative damage, regardless of whether they are created endogenously or obtained exogenously. Dietary and marine-derived antioxidants supplement and strengthen the defenses provided by endogenous antioxidants, especially in times of stress. The interaction of these systems emphasizes the significance of both internal biochemical processes and external dietary sources in the all-encompassing treatment of oxidative stress and the diseases that are linked to it.

3 | MARINE SOURCES OF NATURAL ANTIOXIDANTS

Threats of novel stressors and diseases are expected to exacerbate the expansion of the marine environment. A vast and largely underutilized reservoir of bioactive compounds with distinctive biological activities and structural characteristics is represented by the ocean, which covers over 70% of the Earth's surface. Introducing a new horizon for the extraction and development of natural antioxidants from the sea, the most diverse marine ecosystem. In a variety of disciplines, antioxidants such as vitamin E, vitamin C, peptides, carotenoids, amino acids, terpenoids, sulphated polysaccharides (SPs), phlorotannins, phenolic compounds, and flavonoids have demonstrated significant potential. Diverse physiological and biochemical adaptations have been developed by marine organisms to endure the harsh conditions of marine habitats, which are characterized by high pressure, low temperatures, limited nutrients, and intense competition for space and resources. These modifications have led to the development of a diverse array of compounds that are both physiologically active and structurally diverse, with a significant number of them demonstrating antioxidant properties. The subsequent discourse delves into the primary marine source of natural antioxidants, with a particular emphasis on marine macro-organisms (Table 3) and microorganisms (Table 4).

3.1 | Marine macro-organisms

3.1.1 | Seaweeds (marine macroalgae)

Seaweeds, which are unicellular or multicellular organisms that live in water or humid conditions, are among the most prevalent sources of marine antioxidants. Seaweeds are generally found in the littoral zone and vary greatly in size, shape, color, and content. The presence of chlorophyll, an organic pigment that can absorb and channel the energy of sunlight, is responsible for the capacity to carry out photosynthesis, which is the transformation of luminous energy into chemical energy. In the course of organic synthesis, these organisms produce gaseous oxygen (O2) and absorb carbon dioxide (CO2) to create complex organic compounds (along with water and mineral salts). Seaweeds have long been used as animal feed. In various regions of several nations, fresh seaweed food is still commonly fed to horses, cattle, and sheep [33]. Seaweed is one of the most plentiful sources of marine antioxidants. These photosynthetic organisms include, for example, brown algae (Phaeophyceae), red algae (Rhodophyceae), and green algae (Chlorophyceae). Each group generates a variety of bioactive molecules with antioxidant properties. Red algae contain agars, carrageenans, xylans, sulphated galactans, and porphyrans; green algae contain xylans and sulphated galactans; and brown algae contain alginates, sulphated fucose-containing polymers, and laminarin. Sulfated polysaccharides called fucoidans, which are made by brown algae, have significant antioxidant properties through several processes, including metal chelation, direct radical scavenging, and the strengthening of endogenous antioxidant defenses. The antioxidant qualities of red seaweeds include agar, sulfated galactans, and crude protein (up to 50%). However, up to 30% of green seaweeds are quite high in protein. Numerous bioactive compounds with antioxidant properties, including polysaccharides like ulvans, carotenoids, and chlorophylls, are present in them. Variables that impact seaweed's antioxidant capability include species, location, season, ambient conditions, and extraction methods. The antioxidant activity of brown algae is often higher than that of red and green algae due to their higher content of polyphenolic chemicals [34].

Table 3. Marine sources (macro-organism) of natural antioxidants.

Source Organism	Key Bioactive Compounds	Antioxidant Mechanisms / Properties
Seaweeds	Brown algae	The antioxidant activity of brown algae is often higher than that of red and green algae due to their higher content of polyphenolic chemicals.
	Red algae	Contains crude protein (up to 50%).
	Green algae	Up to 30% of green seaweeds are quite high in protein.
Sea Cucumbers	Esterified phospholipids	Strong radical scavenging and metal chelation. Activity linked to the degree of sulfation and phenolic content.
Fishes	Proteins	Radical scavenging, inhibition of lipid peroxidation.
	Peptides	Bioactive peptides combat free radicals.
	PUFAs	PUFAs provide systemic antioxidant protection.
Marine invertebrate	Sponges	Radical scavenging (DPPH, ROS assays).
	Corals	Chemical defense compounds with antioxidant properties.
	Mollusks	Mollusks (oysters, mussels, clams) counter oxidative stress from filter feeding.

3.1.2 | Sea cucumbers

Sea cucumbers (Holothuroidea) and their extracts have drawn a lot of attention from researchers and nutritionists due to their nutritional content, potential health advantages, and use in the treatment of chronic inflammatory illnesses. Around the world, sea cucumbers have long been used for both culinary and medical purposes. Water cucumbers, nutrient-dense creatures found in the deep water, have been used as food and medicine by people in Korea, Japan, Indonesia, and China since ancient times. Special components found in sea cucumber extracts include modified triterpene glycosides, sulfated polysaccharides, esterified phospholipids, and glycosphingolipids. Through radical scavenging and metal chelation, they also exhibit potent antioxidant qualities. Sea cucumber extracts' antioxidant activity has been connected to the amount of polysaccharide sulfation and overall phenolic content [35].

3.1.3 | Fishes

The biochemical, physiological, and developmental systems that govern life can be better understood by researching how marine fish respond to natural challenges. This is why they are a valuable source of antioxidants. Some of the antioxidant-rich components found in fish cells include proteins, peptides, amino acids, and polyunsaturated fatty acids. Some bioactive peptides in hydrolysates are extremely effective at combating free radicals. These peptides include 3-20 amino acid residues and operate as antioxidants in a variety of ways, including eliminating radicals, chelating metals, and inhibiting lipid peroxidation. For example, heat shock proteins in Antarctic fish species have survived for at least 2.5 million years in the absence of external heat stress, while other systems have evolved to mitigate the negative effects of both high temperatures and oxidative stress. Marine fish are also high in polyunsaturated fatty acids (PUFAs), namely omega-3 fatty acids such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). Additionally, fish tissues contain endogenous antioxidant molecules such as coenzyme Q10, carotenoids (especially astaxanthin in salmon), and tocopherols, which contribute significantly to their antioxidant qualities [36].

3.1.4 | Marine invertebrates

Marine invertebrates, including sponges, corals, mollusks, and echinoderms, represent a rich assemblage of species that produce several bioactive chemicals exhibiting antioxidant properties. They are a vital economic asset and serve a fundamental function in food webs and environmental services, embodying a very diversified taxonomic group. Sponges (Porifera) have evolved chemical defense mechanisms to safeguard against rivals, predators, and infections in the marine ecosystem. It is a highly fascinating source of bioactive natural compounds and chemical defenses, possessing antioxidant characteristics [37]. A systematic study of terpenes isolated from marine sponges discovered 17 compounds with notable in vitro antioxidant potential. The various families of terpenes have demonstrated considerable radical scavenging capabilities in assays like DPPH (2,2-diphenyl-1-picrylhydrazyl) and the assessment of intracellular reactive oxygen species (ROS). Sesterpenes and sesquiterpenes represent prominent examples. A varied range of substances from several chemical classes, including alkaloids, peptides, and polyketides, has been found in the crude extract of recognized organisms. Compounds with significant antioxidant activity have been discovered in species such as Haliclona sp., Xestospongia sp., and Petrosia sp [38]. Both hard (Scleractinia) and soft (Alcyonacea) corals are rich in terpenoids, which are a variety of secondary metabolites of marine animals that include cembranoid diterpenes, polyhydroxylated steroids, and other substances with exceptional antioxidant qualities. Research on the antioxidant chemicals of species such as Lobophytum sp., Sarcophyton sp., and Sinularia sp. has been substantial [39]. After the Arthropoda, the molluscs are the second largest phylum of invertebrate animals, including gastropods, bivalves, and cephalopods. They're called mollusks or similar terms. Many substances have antioxidant qualities, including proteins, peptides, carotenoids, and polysaccharides.

Antioxidant molecules, which are plentiful in oysters, mussels, and clams, help them mitigate the oxidative stress brought on by their filter-feeding habits and exposure to environmental contaminants.

3.2 | Marine microorganisms

The variety of marine microorganisms is immense and includes bacteria, fungi, viruses, microalgae, archaea, and many protozoa. These microscopic creatures are vital to marine environments and represent a vast and mainly untapped source of antioxidant chemicals. With their anti-inflammatory, anti-cancer, skin-brightening, hydrating, and anti-aging qualities, they also have significant therapeutic and cosmetic benefits. They have evolved unique metabolic processes to generate bioactive substances with antioxidant qualities, allowing them to adapt to a range of marine habitats, including deep-sea hydrothermal vents and surface waters.

3.2.1 | Microalgae

The greatest primary biomass, marine microalgae, has drawn interest as a source of novel compounds and genes with potential applications in biotechnology. A wide range of microalgae can be found in the diverse marine environment. These organisms generate proteins, fatty acids, pigments, and polysaccharides, among other bioactive substances with antioxidant qualities. Among the most powerful antioxidant substances that microalgae produce are carotenoids, specifically astaxanthin, β-carotene, lutein, and zeaxanthin. In terms of sustainable energy sources, microalgae are a potential substitute for fossil fuels and help achieve important Sustainable Development Goals (SDGs). As a carbon-negative energy source that may be used in many coastal areas across the world, marine microalgae, in particular, have the potential to significantly contribute to sustainable development. Because they develop more quickly than terrestrial cereal plants, these plants are also recognized as prospective feedstocks for chemicals and biofuels. Microalgae also produce a range of phenolic chemicals with strong antioxidant qualities, including flavonoids, isoflavones, and phenolic acids. There is evidence that species like Phaeodactylum tricornutum, Chlorella vulgaris, and Spirulina platensis have phenolic compounds with strong radical scavenging properties [40]. Sustainable development is made possible by microalgae's ability to sequester CO_2, improve food production, purify wastewater, guarantee energy security, and advance economic growth. Microalgae are widely used to produce biofuel and can be used to achieve several other objectives, such as carbon sequestration, wastewater treatment, food production, and the creation of products that could improve the welfare of a country. Fossil fuel consumption is nearing its peak and is a major contributor to current global greenhouse gas emissions and related climate change. Microalgae biofuel can partially replace this consumption [41].

3.2.2 | Marine bacteria

Marine bacteria could be a source of new protective molecules as well as chemicals that are useful for the body. These bacteria can live in several different sea environments that are cold, dark, and under a lot of pressure. Interestingly, a lot of very different organisms do very well in these places and make natural goods that are very interesting and complicated. They make antioxidants like carotenoids, carbohydrates, enzymes, and amino acids that are similar to mycosporine [42]. So far, only a few microorganisms have been studied for bioactive metabolites, even though a huge number of active chemicals have been found, some of which have unique structural skeletons. Certain types of bacteria, including Agrobacterium aurantiacum, Brevibacterium sp., and Paracoccus haeundaensis, make a lot of protective carotenoids. Marine bacteria are thought to be better at bioremediation of heavy metals, hydrocarbons, and many other chemicals and xenobiotics that are tough because they form biofilms and make extracellular polymeric substances. Bioremediation can be done by a lot of different sea bacteria. When marine bacteria are used for bioremediation in situ, the organisms can be used directly in any bad climate without having to be genetically modified. Polysaccharides from marine microorganisms, particularly exopolysaccharides (EPS), possess significant antioxidant properties. The antioxidant capabilities of these polysaccharides are frequently augmented by specific structural features such as sulfate groups and uronic acids. Substantial quantities of polysaccharides such as laminarin, xylan, and chondroitin sulfate exist in the ocean, and marine microbes possess enzymes capable of degrading these polysaccharides. Estimates suggest that 5-15 billion metric tons of laminarin, an energy-storing chemical produced by diatoms, are generated annually [43].

3.2.3 | Fungi

Another important source of novel bioactive substances with antioxidant properties is the marine-derived fungus. They inhabit silt, saltwater, and marine life, among other maritime environments. As a rich source of structurally diverse bioactive chemicals, fungi are important in marine bioprospecting. Particularly in deep-sea hydrothermal communities, numerous studies have uncovered a variety that was previously unthinkable. In addition, they generate a variety of well-known bioactive substances, including molecules with antiproliferative properties and antiviral, anticancer, antibiotic, and antiangiogenesis chemicals. From shallow water to the deep sea, and even on polar ice sheets, maritime mushrooms can be found in a variety of maritime environments. Many organic materials, both living and dead, contain them. Remarkably, a vast array of antioxidant chemicals has been discovered that have potential use in a variety of sectors, such as food, medicine, and cosmetics. Studies that rely on cultivation have shown how common fungi are in marine macro-organisms like algae and sponges [44]. Numerous natural antioxidants, such as polysaccharides, phenolic compounds, terpenoids, pigments, peptides, sterols, phenolics, alkaloids, and flavonoids, have been shown to be found in fungi. Marine fungi produce phenolic compounds, including flavonoids and phenolic acids, which are among the most potent antioxidants. Numerous phenolic compounds with potent radical scavenging capabilities are produced by Aspergillus species, Penicillium species, and Fusarium species. DPPH, ABTS, hydroxyl, superoxide, hydrogen peroxide, and nitric oxide radicals can all be scavenged by antioxidants produced from fungi in vitro [45].

Table 4. Marine sources (microorganisms) of natural antioxidants.

Source Organism	Key Bioactive Compounds	Antioxidant Mechanisms / Properties
Microalgae	Carotenoids, proteins, polysaccharides, fatty acids, phenolic acids, flavonoids	• Potent radical scavenging, singlet oxygen quenching • Phenolic compounds enhance activity • CO_2 sequestration, wastewater treatment, food/feed, • biofuels (sustainability + antioxidant role)
Marine Bacteria	Carotenoids, enzymes, Exopolysaccharides (EPS)	• Radical scavenging, metal chelation, ROS reduction • EPS enhanced by sulfate groups and uronic acids • Biofilms aid bioremediation of metals and xenobiotics
Fungi	Polysaccharides, phenolic acids, flavonoids, terpenoids, pigments, peptides, sterols, alkaloids	• Strong scavenging: DPPH, ABTS, hydroxyl, H_2O_2, • superoxide, NO radicals • Phenolic compounds are particularly potent • Found in sediments, macro-organisms (sponges, • algae), mangroves
Sponges and associated bacteria	Terpenoids, alkaloids, peptides, polyketides; microbial metabolites from sponge bacteria	• Radical scavenging, antioxidant defense • Symbiotic bacteria are major producers of bioactive compounds. • Also antibacterial, antifungal, antiviral

3.2.4 | Sponges and associated bacteria

Marine sponges are the first known multicellular invertebrate species found in the marine environment. The fossil record of the Phylum Porifera dates back more than 600 million years, making it one of the oldest groups of metazoans. Additionally, they are a rich source of interesting chemicals that have uses in the food, cosmetic, pharmaceutical, nutraceutical, and other significant industries. Its biological and chemical diversity is abundant. Researchers have been looking for novel bioactive molecules for a while to address the toxicity of already used substances, the underlying problems of drug resistance, and the increasing incidence of severe illnesses. The most prevalent source of bioactive chemicals, such as antiviral, antibacterial, and antifungal compounds, among all marine life is found in sponges. In reality, the microorganisms associated with the sponges—particularly the bacteria—produce many of these bioactive chemicals instead of the sponges themselves.

3.3 | Sponges as sources of antioxidants

The soft-bodied, sessile, spineless creatures known as sponges filter feed by collecting microscopic particles from saltwater that rises through their bodies. Antioxidant qualities are among the many pharmacological actions exhibited by the chemical and bioactive components found in abundance in these foods. They contain a variety of compounds that have shown strong radical scavenging abilities in tests like DPPH (2,2-diphenyl-1-picrylhydrazyl) and intracellular ROS measurement. These compounds include phenol, flavonoids, phenolic acid, polyphenol, tannin, steroids, saponins, glycosides, and more.

3.3.1 | Peptides and Proteins

Multifunctional marine bioactive peptides (MBPs) that are produced by marine sponges have antioxidant qualities. When these substances are antioxidants, it's usually because they have special amino acid sequences and combinations. These are bioactive peptides (BPs): amino acid-based chemical compounds joined by covalent bonds (like amide or peptide bonds). Due to their natural origin, some peptides are free to exist. In contrast, most peptides are surrounded by or coded with their own parent protein units. Aquatic microbes, such as sponges, microalgae, bacteria, fungi, and marine polysaccharides, are thought to be rich sources of amino acids [46]. Amino acids have a basic structure and function that includes a carboxyl group, an amine group, hydrogen, and different R groups. Finding cyclic peptides in marine sponges is widespread, especially those with unusual amino acids. These peptides often have important antioxidant properties. When taken from the sponge *Discodermia kiiensis*, discodermins show strong antioxidant properties and help prevent damage caused by reactive stress. A similar example is jaspamides, which are derived from the sponge *Jaspis sp.* and have strong protective properties in a number of ways. To make biological settings stronger in the 21st century, marine bioactive peptides with tunable functional and structural features, as well as bioactive traits with clinical and therapeutic value, are desired [47].

3.3.2 | Glycoside

Additionally, marine sponges (Phylum: Porifera) are among the most prolific producers of bioactive secondary metabolites. The development of intricate chemical defenses, such as glycosides, has been provoked by their sessile lifestyle in competitive ecosystems. These compounds, which are distinguished by a sugar moiety (glycone) that is connected to a non-sugar component (aglycone), are a significant category of marine natural products that have pharmacological significance. Sponge-derived glycosides have been known to possess antimicrobial, antiviral, immunomodulatory, and anticancer properties, as they exhibit a remarkable structural diversity that encompasses glycolipids, triterpene saponins, and steroidal glycosides [48] .

3.3.3 | Flavonoids

Flavonoids in marine sponges are synthesized either by symbiotic bacteria or through sponge-associated metabolic pathways. They demonstrate significant antioxidant activity, counteracting reactive oxygen species (ROS) produced in challenging marine conditions. Sponge-derived flavonoids exhibit antibacterial, anti-inflammatory, and cytotoxic activities, positioning them as interesting candidates in pharmacological research [49]. Certain studies suggest their efficacy in anticancer treatments by promoting apoptosis and suppressing tumor cell growth. Their propensity to absorb UV radiation indicates a protective function against solar radiation in shallow-water sponges. Notwithstanding their potential bioactivities, flavonoids in marine sponges are less investigated than alkaloids and glycosides [50].

3.3.4 | Tannin

Marine sponges have been reported to contain tannins, a kind of polyphenolic compounds that are more frequently found in terrestrial plants. These substances have the capacity to precipitate alkaloids and bind proteins, which may offer a chemical defense mechanism against fouling organisms and predators. Strong antioxidant qualities are exhibited by marine sponge tannins, which aid sponges in overcoming oxidative stress in dynamic marine environments. Additionally, they have antibacterial properties, which prevent the growth of fungi, bacteria, and microorganisms that create biofilms. According to certain research, they may be used in anticancer treatments by causing apoptosis and preventing the proliferation of malignant cells. In marine environments, their ability to chelate metals aids in ecological balance and purification. Additionally, tannins might influence the microbial communities connected to sponges through symbiotic relationships. When compared to other secondary metabolites, tannins from marine sponges are still poorly understood, despite their biological significance. There is currently little knowledge about their structural diversity and biosynthetic origin. Tannins from sponges, however, offer a promising source of new medicinal compounds [49].

3.3.5 | Saponins

Marine sponges contain saponins, amphiphilic glycosidic molecules with a hydrophobic aglycone and hydrophilic sugar chains. Sponge triterpenes or steroidal glycosides protect against predators, infections, and biofouling. Their powerful surface-active characteristics break cell membranes, causing substantial antibacterial and antifungal effects. Several sponge-derived saponins induce apoptosis and decrease tumor cell growth. Saponins can also inhibit viral multiplication and entrance. Saponins discourage marine fish and invertebrate predators beyond their pharmaceutical purpose. The sponge holobiont's symbiotic equilibrium is also maintained via microbial community regulation [51]. Sponge saponins' biosynthesis and structural diversity are understudied despite their relevance. Marine sponge saponins are interesting bioactive compounds with medicinal promise.

3.3.6 | Steroids

Sterols, typically glycosylated, are marine sponges' most numerous and structurally varied metabolites. Sponge steroids often have exotic side-chain alterations and oxygenation patterns. These molecules function as chemotaxonomic markers to classify sponge groups and genera. Sterols from sponges have antibacterial, antifungal, and antiparasitic properties. They induce tumor cell death and limit cancer growth. Other anti-inflammatory and immunomodulatory compounds could be therapeutic leads. Some sponge steroids suppress HIV and herpes simplex virus. Chemical changes that improve pharmacological potential have been sought due to their structural originality. Their biosynthetic processes and supply remain unclear despite their promise. In general, marine sponge steroids are a rich source of new biological drugs [52].

3.3.7 | Phenolic compounds

Marine sponge secondary metabolites include phenolic chemicals, which are usually found in terrestrial plants. These chemicals have significant antioxidant properties due to hydroxyl groups on aromatic rings. In sponges, phenolics neutralize ROS from excessive salinity, UV exposure, and pollution. Several sponge-derived phenolics are antibacterial and antifungal, safeguarding the host [49]. Some phenolic substances induce apoptosis and suppress tumor development in cancer cell lines. Anti-inflammatory effects are due to pro-inflammatory mediator regulation. As metal chelators, phenols may reduce seawater metal ion oxidative damage. These chemicals defend against predators and biofouling organisms. Sponge phenolic metabolites are less studied than alkaloids, glycosides, and steroids. Phenolic chemicals from sea sponges may be promising medicinal leads [49].

3.3.8 | Terpenes and terpenoids

Terpenes and terpenoids are marine sponge secondary metabolites with the largest diversity and study. The biosynthesis of isoprene units (C5 building blocks) produces monoterpenes, sesquiterpenes, diterpenes, and triterpenes. Sponge terpenoids often undergo halogenation, rearrangements, and oxygenation, which are rare in terrestrial species. Chemical defenses against predators, fouling species, and microbial diseases in marine habitats. Biologically, sponge terpenes and terpenoids are potent antibacterial, antifungal, and antiviral [38]. Diterpenes and triterpenoids are attractive chemotherapeutic options due to their cytotoxic and anticancer properties. Terpenoids affect cellular signaling pathways with anti-inflammatory and immunomodulatory characteristics [53]. Symbiotic sponge-associated bacteria may help terpene production. Sustainable gathering and structural characterization of these complex compounds remain difficult despite their abundance. Marine sponge terpenes and terpenoids provide unique bioactive chemicals for medicinal and biotechnological uses [32].

3.4 | Applications of marine antioxidants

Marine-derived chemicals are increasingly being used in various industries due to their high antioxidant effects and distinctive architectures. Because marine antioxidants are so effective at reducing oxidative stress and neutralizing free radicals, they are used in a wide range of industries. For oxidative stress-related issues, such as food preservation, medication manufacturing, cosmetics manufacturing, and nutraceutical manufacturing, marine antioxidants hold promise.

3.4.1 | Uses in the food industry

The utilization of natural bioactive compounds as functional additives in food items has gained popularity recently due to their numerous health advantages. Food spoils due in large part to oxidation. It produces molecules that are toxic and alter the flavor, texture, color, and nutritional value in undesirable ways. Marine biopolymers that decompose naturally and are safe for mammals include gelatin, alginate, carrageenan, chitin, and chitosan. They are also employed extensively in a variety of industries. These biopolymers have a variety of uses in food, including thickening and gelling water-based solutions, stabilizing foams, emulsions, and dispersions, preventing the formation of sugar and ice crystals, preventing food from spoiling, and regulating the release of excess materials [54]. Functional Food Components Functional beverages, dairy products, and baked goods are enhanced with the addition of thickness, stability, and gelation by marine polysaccharides, particularly sulfated polysaccharides such as carrageenans and fucoidans, which also impart antioxidant properties. Marine antioxidants are incorporated into foods as functional ingredients to enhance their nutritional value and health benefits, in addition to their preservation purpose [54]. Food packaging is one example of a food contact material (FCM). Their significance for food safety and quality cannot be overstated. Food packaging frequently uses plastic, yet this harms the ecology, wildlife, and the environment. Alternative polymers that are comparable to plastic but more environmentally friendly (biodegradable) are thus the subject of numerous research investigations at the moment [55].

3.4.2 | Uses in the pharmaceutical field

Marine-derived chemicals possess potent antioxidant properties and a diverse array of biological activities, rendering them promising candidates for medicinal applications, particularly in the prevention and treatment of disorders associated with oxidative stress. Various marine ecosystems possess varying concentrations of carbohydrates. Polysaccharides, a category of carbohydrates, play a significant role in various sectors, including food manufacturing, pharmaceuticals, and cosmetics. Globally, cardiovascular diseases (CVDs) rank among the worst illnesses. Severe adverse effects, including hypotension, sluggish heart rate, irregular heartbeats, and shifts in ion levels, are now associated with the sole therapy option [56]. Bioactive substances derived from plants, microbes, and marine creatures have been trending upwards in popularity as of late. Novel bioactive metabolites with a wide range of pharmacological properties can be found in marine sources.

Mental illnesses that damage the brain. In neurodegenerative diseases like Alzheimer's, Parkinson's, and amyotrophic lateral sclerosis, neurons slowly die because of oxidative stress. Marine antioxidants strengthen the body's own antioxidant protections in neuronal tissues, fight free radicals, and reduce inflammation [57]. Pain and swelling in different parts of the body are known by different names. Like, rhinitis is swelling in the nose, asthma is swelling in the lungs, arthritis is swelling in the joints, and dermatitis is swelling on the skin. When the body gets an infection, it starts to swell. This is also the first step in healing a wound. It's what makes the defense system work. It is possible for inflammation to become chronic, though, which means that the immune system is always working and the inflammation doesn't go away. Fucoidans from brown algae have been shown to lower inflammation in several preclinical models [58]. Sometimes, these sulfated polysaccharides can stop white blood cells from going to the site of inflammation. They can also lower the release of cytokines that cause inflammation and change the way immune cells work, all of which could reduce swelling and tissue damage [59]. Because fucoidans are antioxidants, they may help fight inflammation by reducing the swelling caused by oxidative stress [60].

Table 5. Applications of marine antioxidants

Industry	Application Area	Details / Examples
Food industry	Food preservation	Marine biopolymers prevent spoilage, stabilize emulsions/foams, inhibit crystal formation, and control additive release.
	Functional food ingredients	Sulfated polysaccharides (fucoidans, carrageenans) in beverages, dairy, and baked goods provide antioxidant benefits + act as stabilizers, gelling agents, and thickeners.
	Edible packaging	Biodegradable marine polysaccharide-based food packaging as an eco-friendly alternative to plastic.
Pharma-ceuticals	Cardiovascular diseases	Marine bioactive compounds show cardioprotective potential with fewer side effects than current therapies.
	Neurodegenerative diseases	Protect neurons from oxidative stress in Alzheimer's, Parkinson's, and ALS; reduce inflammation.
	Inflammatory diseases	Fucoidans reduce cytokine production, leukocyte recruitment, and oxidative stress-induced inflammation.
	Cancer (implied)	Marine antioxidants support anticancer strategies via oxidative stress regulation.
Cosme-Tics	Anti-aging products	Algae-derived proteins, amino acids, fatty acids, vitamins, and minerals are used for skin health and anti-aging.
	Skin care products	Marine antioxidants with tyrosinase inhibitory activity reduce hyperpigmentation and even skin tone.
	Hair care products	Protect hair proteins, lipids, and pigments from oxidative stress due to UV, pollution, and styling.
Nutra-Ceuticals	Dietary supplements	Natural polysaccharides with antioxidant activity are used in health supplements.
	Medical foods	Marine macroalgae metabolites (SPs, phlorotannins) reduce cancer risk and related diseases.
Future trends	Sustainable production	Aquaculture of seaweeds/microalgae, closed-loop cultivation for an eco-friendly supply.
	Delivery systems	Enhanced bioavailability, stability, and targeted delivery of marine antioxidants.
	Personalized solutions	Customized antioxidant supplementation tailored to genetics, lifestyle, health status.

3.4.3 | Uses in Cosmetics

Multiple studies conducted over the past 20 years have shown that sea natural ingredients are good for cosmetics due to their special qualities that land-based organisms do not possess. As a result, many bioactive substances and ingredients derived from marine sources are being created, used, or thought about for skin care and cosmetics. Natural aging makes many body systems worse over time. The function of cells decreases, and diseases linked to getting older start to show up. Research has shown that algae, including both macroalgae and microalgae, contain proteins, amino acids, fatty acids, vitamins, and minerals that are good for people to eat and for medical uses [61]. By lowering the amount of melanin in the skin, skin lightening uses natural or man-made items to make the skin tone lighter or more even. As a result, skin-lightening goods aid people who have skin issues. To even out skin tone and lower hyperpigmentation, skin-whitening products contain marine vitamins that stop tyrosinase from doing its job [62]. Marine antioxidants are also found in hair care products to protect hair from damage caused by smog, UV rays, and styling tools. Oxidative stress can damage the proteins, lipids, and colors in hair. This can make hair break, look dull, and turn gray too quickly.

3.4.4 | Uses as nutraceuticals

Marine species have consistently constituted a component of the human diet, particularly in Eastern cultures. They are recognized for their health benefits since they provide vitamins, minerals, polyunsaturated fatty acids (PUFAs), amino acids, dietary fibers, and many bioactive compounds [63]. Natural polysaccharides, a category of biomacromolecules with high biocompatibility, are extensively utilized in biomedical and therapeutic applications due to their efficacy in combating free radicals [64].

3.4.5 | Future Outlook

In the next few years, marine antioxidants will likely be used in a lot more ways as extraction technologies, methods for figuring out their structures, and transport systems get better. It is important to find environmentally friendly ways to make marine antioxidants as the need for them rises. The climate should grow seaweeds and microalgae in water rather than gathering them from the. More than that, it makes sure that these things will always be available. You can make things even more sustainable by using fewer resources and creating less waste with closed-loop cultivation systems that reuse water and chemicals. The efficacy of marine antioxidants in a variety of applications depends on both their intrinsic properties and how well they reach particular target locations. To improve marine antioxidants' stability, bioavailability, and ability to target certain regions, researchers are developing novel delivery vehicles. For application in medications and supplements, researchers are developing tailored delivery methods that can deliver marine antioxidants to particular tissues or cell types. Antioxidant supplementation is currently being approached from the perspective of tailored medicine and nutrition. This is because more and more people are becoming aware that different people react differently to antioxidants depending on their health, lifestyle, and DNA. Because of their diverse structures and modes of action, marine antioxidants enable the creation of customized antioxidant solutions that are tailored to the demands of each individual.

4 | CONCLUSION AND PERSPECTIVE

This thorough review has examined the varied realm of marine-derived antioxidants, emphasizing marine biota and polysaccharides. In conclusion, marine-derived antioxidants represent a promising and largely unexplored resource for combating oxidative stress and its associated diseases. Marine organisms, through their unique biochemical adaptations to harsh environments, produce a diverse array of bioactive compounds with potent antioxidant properties. These compounds, including polysaccharides, phenolic acids, terpenoids, and peptides, not only exhibit strong antioxidant activity but also offer multiple therapeutic benefits across various sectors, including pharmaceuticals, cosmetics, food, and nutraceuticals. The review emphasizes the significance of marine biota, such as seaweeds, sponges, and microorganisms, as valuable sources of novel antioxidants. Furthermore, marine antioxidants hold promise in addressing oxidative stress-related conditions, including cancer, cardiovascular diseases, and neurodegenerative disorders. The increasing interest in sustainable extraction methods and closed-loop cultivation systems for marine organisms ensures the future availability of these valuable bioactive compounds. With advancements in biotechnological research and targeted delivery systems, marine-derived antioxidants have the potential to be integrated into personalized medicine and health solutions. As the search for effective antioxidants intensifies, marine organisms will continue to play a critical role in advancing the field of oxidative stress management and therapeutic development, offering new hope for human health and well-being.

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