

# Natural Antioxidants: A Comprehensive Review of Plant, Animal, and Mineral-Derived Sources, Structures, and Mechanisms

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## Abstract

Natural antioxidants play a critical role in maintaining cellular homeostasis by neutralizing reactive oxygen species (ROS) and preventing oxidative damage. This comprehensive review explores antioxidants derived from plant, animal, and marine sources, emphasizing their structures, mechanisms of action, and therapeutic applications. Plant-based antioxidants, including polyphenols, flavonoids, and carotenoids, are widely studied for their potent free radical scavenging properties. Animal-derived antioxidants, such as enzymatic (superoxide dismutase, catalase) and non-enzymatic compounds (coenzyme Q10, carnosine), contribute to cellular defense against oxidative stress. Marine sources, including algae and seafood-derived bioactives like astaxanthin and fucoidans, provide unique antioxidant properties with promising health benefits. The review also presents comparative insights into the bioavailability, effectiveness, and challenges associated with these natural antioxidants. Understanding their mechanisms and potential applications can aid in developing antioxidant-based therapeutic strategies for aging, cardiovascular diseases, and metabolic disorders.

**Keywords:** Plant antioxidants, animal antioxidant, marine antioxidant, cancer, diabetic, metabolic disorders

## 1. Introduction

Antioxidants are chemical compounds that inhibit oxidation, thereby protecting biological systems from oxidative damage. Halliwell and Gutteridge define an antioxidant as “any substance that significantly delays or inhibits oxidation of that substrate when present at low concentrations compared to those of an oxidizable substrate” [1]. In biological systems, antioxidants counteract oxidative stress, which occurs when prooxidants accumulate faster than the body can neutralize them, leading to cellular damage. Oxidative stress is linked to several chronic diseases, including heart disease and diabetes [2]. Antioxidants can be categorized as natural or synthetic. Naturally occurring antioxidants are found in plants, animals, and marine sources, while synthetic antioxidants are often added to food products to prevent lipid peroxidation. They function primarily through two mechanisms: primary antioxidants, which donate electrons to neutralize free radicals, and secondary antioxidants, which prevent oxidative damage by scavenging singlet oxygen, absorbing UV light, and breaking down peroxides into stable products [3].

Chemically produced antioxidant are frequently added to food as preservatives to stop lipid peroxidation. These antioxidants, sometimes referred to as primary and secondary antioxidant, primarily function through two distinct mechanisms. Primary antioxidant, which fall into three categories - free radical terminators, oxygen scavengers, and chelating agents - void the production of free radical. The hydroperoxides produced during lipid oxidant are broken down into stable end products by secondary antioxidant such as thiodipropionic acid and dilauryl theodipropionate. Antioxidants can fight with free radical before they target hosted cells. The function of antioxidants can be defined through several mechanisms such as grabbing harmful molecules, stopping metals from causing damage, preventing a bad chain reaction, and maintaining oxygen levels in appropriate proportions. [4]

A wide variety of plant-based antioxidants are carotenoids, ascorbic acid, anthocyanins, phenolic compounds, gallic acid, and caffeic acid etc. [5] are the bioactive compounds are widely used in traditional foods and medicinal preparations. Additionally, they have applications in preserving meat and meat-based products by inhibiting oxidative stress, thereby improving shelf life and maintaining quality [9]. Natural antioxidants, particularly phenolic compounds from plants, have shown potential in preventing diseases such as cancer, cardiovascular disorders, and inflammation. The polyphenols found in plant seeds, fruits, cereals, and legumes are especially rich in antioxidants, primarily concentrated in their outer layers [10]. Animal-derived antioxidants, such as certain proteins and peptides, also contribute to antioxidant activity. Enzymes like superoxide dismutase (SOD) and catalase, along with bioactive peptides, offer protective effects against oxidative damage (as shown in Fig.1. These compounds have potential applications in

reducing inflammation and improving metabolic health. Marine-based antioxidants, sourced from algae, fish, and marine microorganisms, provide unique bioactive compounds with strong antioxidant potential. In the food industry, synthetic antioxidants are widely used as substitutes for natural antioxidants due to their stability and cost-effectiveness. However, natural antioxidants such as anthocyanins are preferred, as they not only improve the color of meat products but also enhance their antioxidant potential. Given the increasing demand for natural food preservation methods, the study of plant, animal, and marine-derived antioxidants is crucial for their integration into food, pharmaceuticals, and nutraceuticals. There are several reviews that have broadly discussed the general mechanisms of antioxidants, the present review provides a comprehensive and structured analysis of different antioxidants obtained from natural sources, detailing their specific structures and mechanisms of action, rather than describing a common antioxidant mechanism. Furthermore, this review highlights the individual biological activities of these compounds beyond their antioxidant properties, offering deeper insight into their therapeutic potential. By compiling this extensive dataset, this review serves as a valuable resource for researchers, food scientists, and healthcare professionals seeking to explore the multifaceted benefits of natural antioxidants [11].

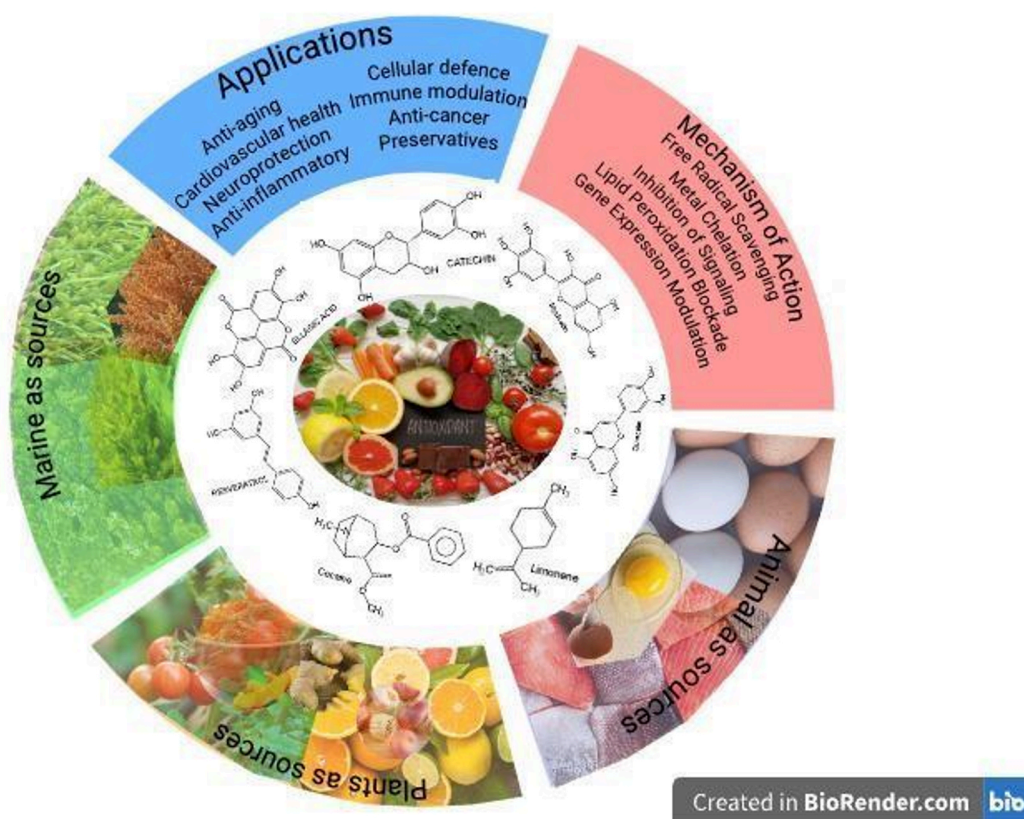


Fig. 1: The image illustrates various plant, animal, and marine sources, along with their applications and mechanisms of action, for natural antioxidants available.

## 2. MECHANISM OF ACTION

Free radicals are highly reactive molecules with unpaired electrons in their outer orbitals, making them capable of oxidizing or reducing other biomolecules within the body. These radicals are primarily generated as byproducts of aerobic respiration, where the mitochondrial electron transport chain serves as a major source of reactive oxygen species (ROS) [12]. During immune responses, activated neutrophils and macrophages produce superoxide and nitric oxide as part of the phagocytosis process. This typically occurs in response to tissue injury caused by bacterial invasion or other pathological conditions, leading to the destruction of infected bacterial cells as well as surrounding tissues. These reactive species contribute to inflammation, stimulate cellular proliferation, and promote the clonal expansion of fibroblasts and lymphocytes. The endogenous production of ROS occurs due to physiological and pathological conditions such as inflammation, immune system activation, excessive physical exertion, ischemia, neurodegenerative conditions, malignancies, infectious diseases, metabolic disorders, aging etc [13]. Exogenous sources include environmental pollutants

(air and water), smoking, alcohol consumption, certain drugs, heavy metals, radiation exposure, and organic solvents like benzene. These sources contribute to oxidative stress by generating ROS, leading to the oxidative modification of critical biomolecules such as proteins, lipids, and DNA. ROS-induced oxidative damage plays a crucial role in the onset and progression of chronic diseases, including diabetes, cardiovascular disorders, liver diseases, and cancer. The activation of ROS-mediated signaling pathways, such as activator protein-1 (AP-1) and nuclear factor kappa B (NF- $\kappa$ B), triggers the transcription of genes involved in cell growth regulation, inflammation, and oncogenesis. Furthermore, lipid peroxidation compromises membrane fluidity and cholesterol integrity, leading to oxidative damage of nearby proteins and the formation of protein carbonyls. Such oxidative stress-driven modifications are closely associated with neurodegenerative disorders, cancer, and the aging process.[14]

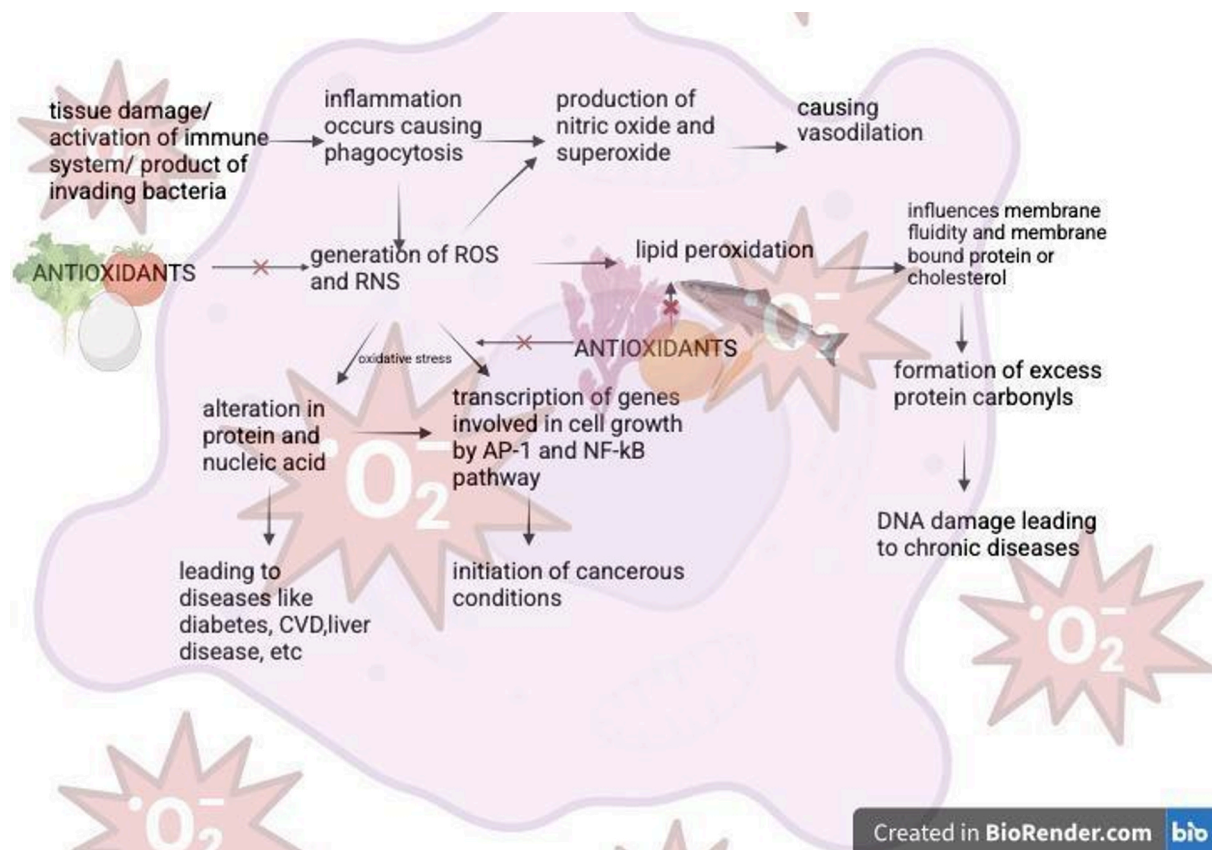


Figure 2: Mechanism of antioxidant (ROS: reactive oxygen species; RNS; reactive nitrogen species and lipid peroxidation; CVD: cardiovascular diseases; DNA: deoxyribonucleic acid; NF- $\kappa$ B: Necrosis Factor- kappa B; AP-1: Activator protein 1; x: the cross on arrow shows inhibition)

### 3. Plant as a source of antioxidant

Plants are rich sources of natural antioxidants, including polyphenols, flavonoids, carotenoids, vitamins (such as vitamin C and E), and other various secondary metabolites. These compounds play a crucial role in neutralizing free radicals, reducing oxidative stress, and preventing cellular damage. These chemicals exhibit a wide range of pharmacological properties, such as anti-inflammatory, anti-cancer, and neuroprotective effects, atherosclerosis, in malignancies etc.[17] The effectiveness of these antioxidants depends on their chemical structure, solubility, and bioavailability. One of the suitable example is the antioxidant potential of phenolic compounds is influenced by their structural characteristics, specifically the number and arrangement of hydroxyl groups, as well as the type of substitutions present on the aromatic rings [18]. These compounds are said to have protective effect as antioxidants, reducing free radicals formation caused by different types of stress. Several plant-based antioxidants are widely used in nutraceuticals, functional foods, and therapeutic formulations. The table 1 provides an overview of key plant-derived antioxidants, their sources, structures, mechanisms of action, and

additional biological activities. The naturally occurring antioxidants are different in their composition, properties, mechanism and site of action. [8]

**Table 1:** Showing the list of plant derived antioxidants

Antioxidant	sources	Mechanism of action	Other activities
Anthocyanin	Found in tissues of plants which are higher encompassing their leaves stems, roots & flowers	Inhibits PI3K, NF-kB, COX-2 pathways Decreases ROS, excitotoxicity.	Neuroprotective, cardioprotective, antidiabetic, anti-cancer and anti-inflammatory.
Lycopene	Tomatoes, Apricots, Watermelon and Pink guava.	Inhibits COX-2, TNF-a. lower NF-kB, MDA levels and LDL.	Antiplatelet, Anti-inflammatory, Anticancer, Anti-diabetic, cardioprotective and neuroprotective.
Vitamin C	Citrus fruits, potatoes, spinach, broccoli, red peppers, strawberries and tomatoes.	Simple diffusion & active transport.	Anti-inflammatory
Vitamin E	Olive and sunflower oils, Avocados, Nuts	Scavenger of free radicals. Inhibition of LDL oxidation	Anti-cancerous. Prevention of Atherosclerosis.
Lutein	Egg yolk, Spinach, and Corn	Activates MRNA, endogenous oxidative system and inhibits IL-1 $\beta$ , IL-6 and MCP-1.	Anti-inflammatory Anti cataract, Severe traumatic brain injury, neuroprotection.
Allicin	Garlic	Work as Oxidizing agent. Induces Nrf-2 system	Antimicrobial. Cardioprotective, neurodegenerative diseases.
Quercetin	Onion	Disrupts bacterial cell wall and alter permeability, inhibits IL-6, IL-8, LOX and COX and induces cell cycle arrest at G2 phase	Anti-cancerous, antiinflammatory and antimicrobial
Catechin	Apples, Strawberries, apricots.	Suppresses COX- 2 enzyme	Anti-cancerous
Gingerol	Ginger	Activates caspase-8, caspase-9, caspase-3, and caspase-7 Inhibits NF-kB, COX-2 and TNF-a.	Anti-inflammatory; Antimicrobial Anti-cancer, asthma and anti-emetic.
Apigenin	Parsley, Onions, oranges and tea.	Regulates p53- Bax- caspase-3 apoptotic pathway. Inhibits aglucosidase activity.	Anti-inflammatory Anti-diabetic.

Curcumin	Turmeric.	Increases antioxidant serum activities like superoxide dismutase, Chemo preventive agent, biosynthesis of cellular matrix proteins.	Anti-inflammatory, Anti-cancer, wound healing.
Chlorophyll	Plants, algae and certain types of bacteria.	Antioxidant activities, modifier of genotypic effect, inhibits CytP450, increase glutathione S-transferase, cell differentiation, cell arrest and apoptosis.	Antimutagens and anticarcinogens.
Cocaine	Erythroxyton coca.	Slows down Progression of neurodegenerative diseases by inhibition of acetylcholinesterase.	Antipsychotic.
Limonene	Citrus rind oil, Dill oil, cumin oil, neroli, bergamot and caraway.	Allures insects with pheromones in them. LOX inhibition, inhibits microbial growth, inhibits RAS oncogene and blocking the G1 cell cycle.	Anti-inflammatory, Anti-microbial and anticancer.
Sulforaphane	Cruciferous vegetables.	Works against ovarian and colon cancer by inhibiting HIF-1 $\alpha$ and VEGF.	Anti-cancer.
Ellagic Acid	Oak bark, Pomegranate.	Able to chelate iron meals such as copper, iron. Inhibits TNF- $\alpha$ and IL-1 $\beta$ .	Antimutagenic, Anti-inflammatory.
Myricetin	Myricaceae, Polygonaceae.	Inhibits Cytochrome P40 & P-Glycoproteins.	Antitumor, Anti-inflammatory, Analgesic and Antidiabetic.
Resveratrol	Peanuts, grapes, berries, pines.	Inactivates COX-2, Activates SIRT and SIRT1.	Anti-inflammatory, Prevent neurodegenerative disorder.

#### 4. Animal as a source of antioxidants

Animal-derived antioxidants consist of enzymatic and non-enzymatic compounds that play a crucial role in maintaining redox balance and protecting against oxidative stress [19]. These antioxidants mitigate the damage caused by reactive oxygen species (ROS) and support overall cellular health. One significant category includes peptides derived from proteins through enzymatic hydrolysis or other physicochemical processes, which exhibit antioxidant properties. The antioxidant activity of these peptides is influenced by factors such as amino acid sequence, composition, and peptide length [20]. Key enzymatic antioxidants include superoxide dismutase (SOD), catalase, and glutathione peroxidase, which serve as primary defense mechanisms against oxidative stress by neutralizing ROS [12]. Additionally, non-enzymatic antioxidants such as coenzyme Q10, taurine, and carnosine play crucial roles in cellular defense by scavenging free radicals and enhancing mitochondrial function [21]. These compounds have significant therapeutic potential in aging, cardiovascular diseases, and metabolic disorders [22]. Bioactive peptides derived from animal proteins exhibit potent antioxidant properties. These peptides are released during digestion or through enzymatic hydrolysis using enzymes such as pepsin, trypsin, elastase, chymotrypsin, proteases, and alcalase [23]. Certain peptides and amino acids also demonstrate

additional health benefits, including anti-inflammatory, hypoglycemic, antithrombotic, and ACE-inhibitory effects, which contribute to human health and disease prevention [24]. Notable antioxidant proteins include ovotransferrin and phosvitins, both of which are found in egg whites and contribute to oxidative stress mitigation through their metal-chelating and radical-scavenging activities [25]. The following table 2 summarizes key animal-derived antioxidants, their sources, structures, mechanism of action, and biological effects.

**Table 2: Animal derived antioxidants**

Antioxidant	Sources	Mechanism of action	Other activities
Ovotransferrin	Egg White.	Through chelating ionic irons it inhibits metal catalysed lipid oxidation.	Antifungal, Antihypertensive, Antiviral.
Phosvitin	Egg yolk.	Through chelating ionic irons it inhibits metal catalysed lipid oxidation.	Antibacterial.
Coenzyme Q10	Salmon & Tuna.	By decreasing prooxidative compounds it decreases lipid peroxidation.	Anti-Inflammatory.
Carnosine	Brain, heart tissues of all vertebrates.	Scavenging of ROS & nitrogen species.	Anti-Inflammatory and Anti-Aggregation.
Astaxanthin	Yeast, Salmon & Algae.	Inhibits NF-kB, TNF-a, IL-6, COX. Increases INF-y, IL-2 and insulin sensitivity.	Anti-inflammatory, Anti-cancer, anti-diabetic and immuno-modulatory activity.

### 5. Marine as a source of antioxidant

Marine organisms, including algae, fish, and invertebrates, are rich sources of bioactive compounds with strong antioxidant properties. These marine-derived antioxidants include carotenoids (such as fucoxanthin), polyphenols, peptides, and polysaccharides, which exhibit potent free radical scavenging activity. Their presence plays a crucial role in protecting marine organisms from oxidative stress in extreme environments [26]. Microscopic and macroscopic algae serve as significant sources of natural antioxidants like tocopherols, polyphenols, and carotenoids. Macroalgae (commonly known as seaweeds) are simple multicellular organisms that thrive in coastal regions and have historically been used for food, animal feed, fertilizers, and traditional medicine, pharmaceuticals, nutraceuticals etc. Recently, seaweeds have gained attention for their industrial applications, particularly as raw materials for producing agar, carrageenan, and alginates, which have functional properties beneficial in pharmaceuticals, cosmetics, and nutraceuticals [27]. Recent studies on marine compound like Astaxanthin and Fucoxanthin also highlight the unique properties like protective against diabetic and liver cirrhosis [28]. Such marine-derived peptides exhibit strong antioxidant activity by inhibiting lipid peroxidation and scavenging reactive oxygen species (ROS) [29]. Marine-derived antioxidants such as

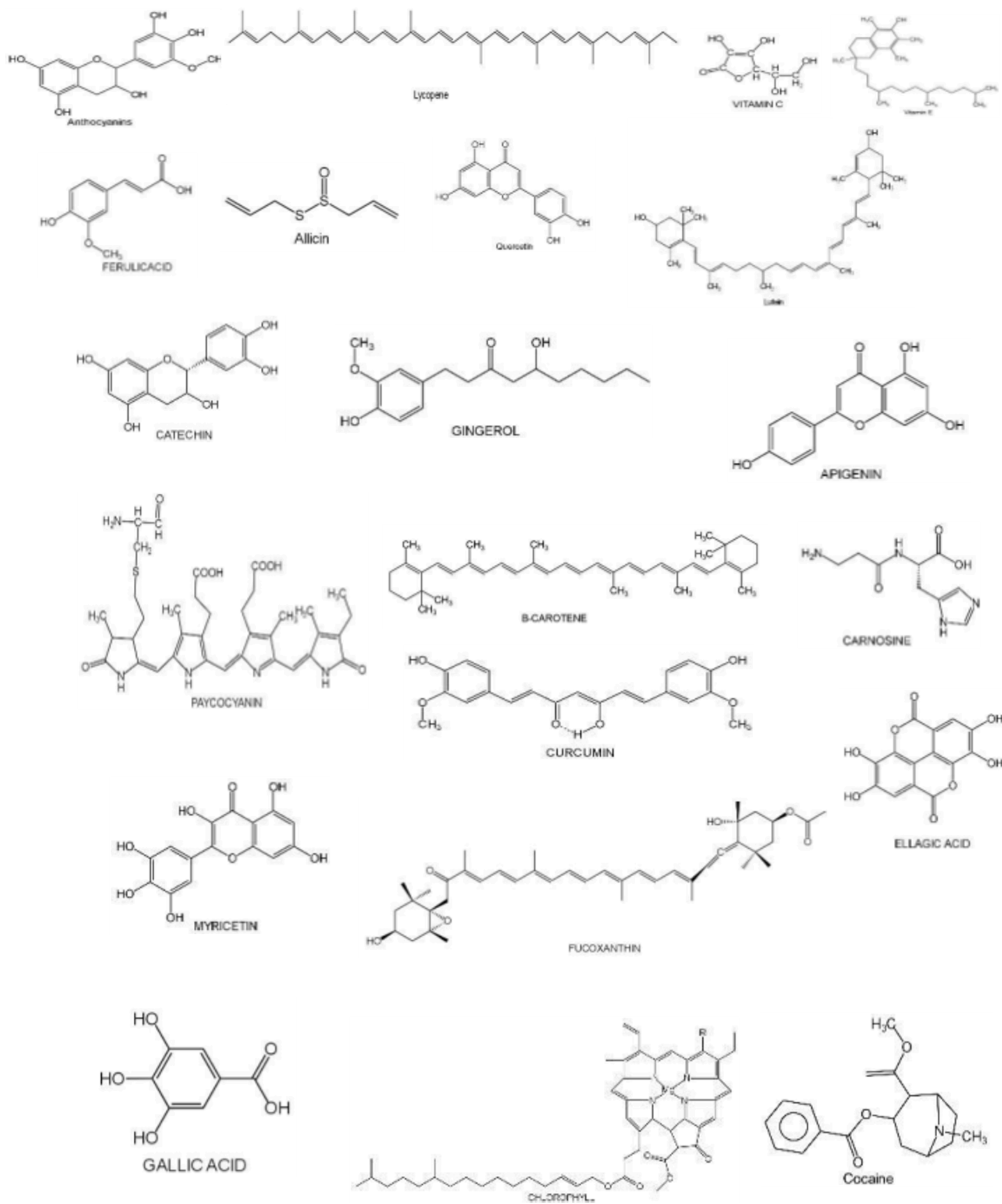
astaxanthin, derived from crustaceans, have been extensively studied for their potent antioxidant and anti-inflammatory effects [30]. The table 3 below provides a comprehensive summary of key marine-derived antioxidants, detailing their sources, chemical structures, mechanisms of action, and additional therapeutic benefits.

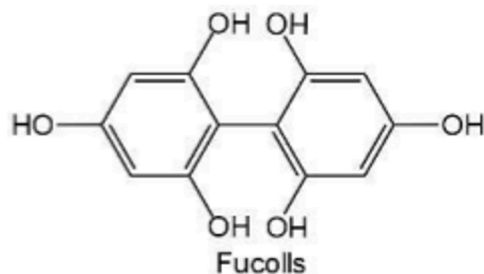
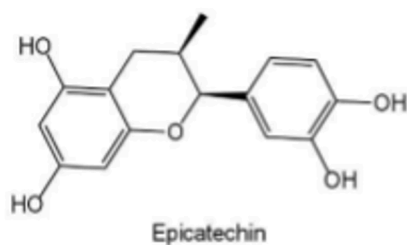
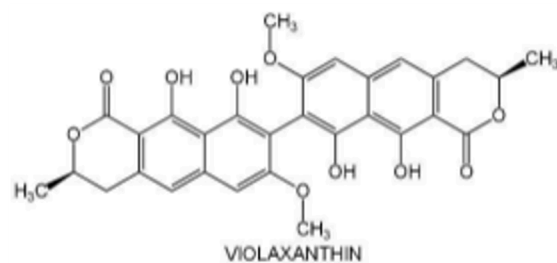
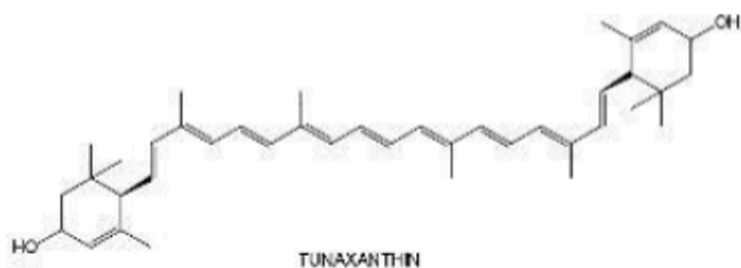
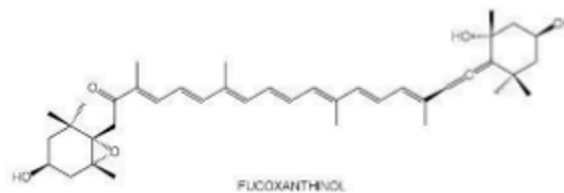
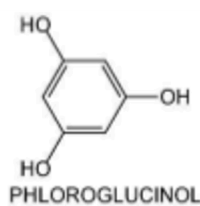
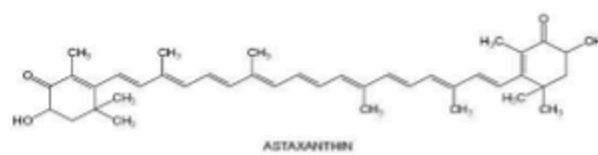
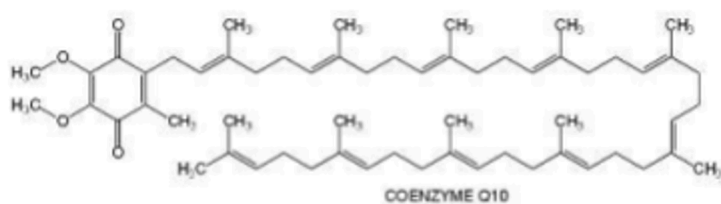
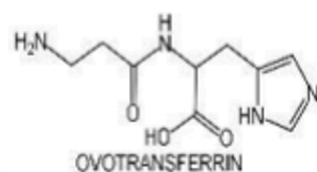
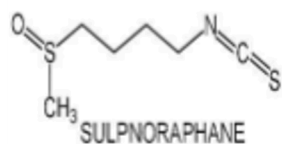
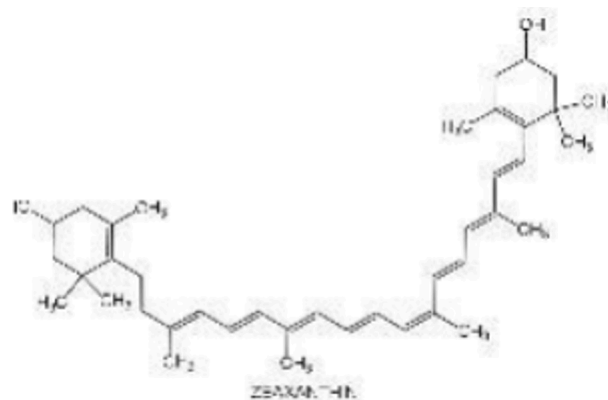
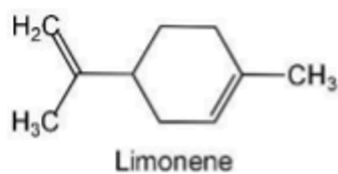
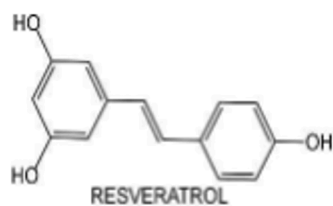
**Table3: Marine derived antioxidant**

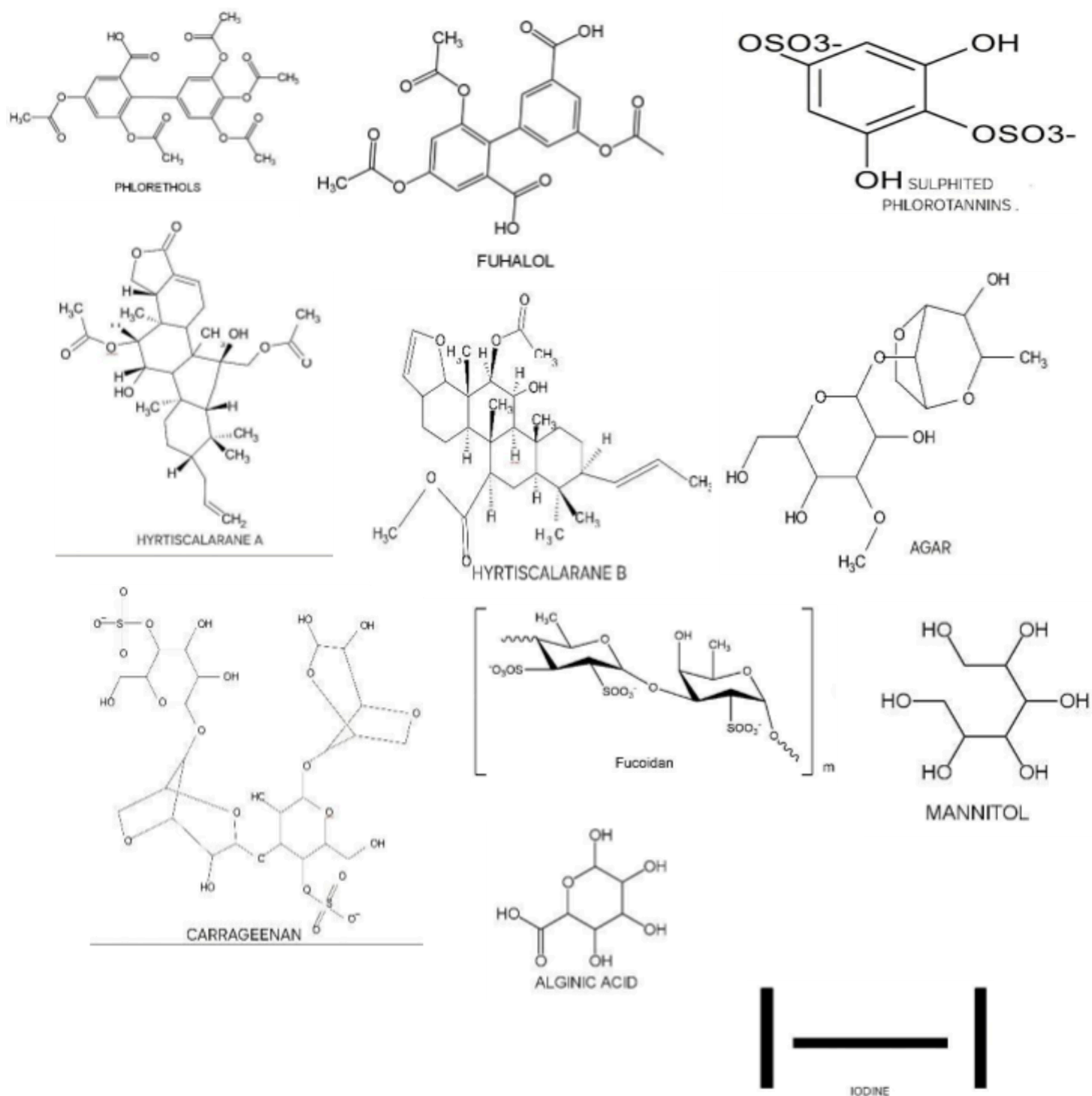
Antioxidant	Sources	Mechanism of action	Other activities
Caffeic acid	F. vesiculosus and F. serratus.	Increases AMPK, GLUT3 and decreases NK-kB, IL-6, IL-8, CRP, MAPK, ahemolysin secretion	Antibacterial, Anti-viral activity, Anti-cancer, anti-diabetic, neurodegenerative activity and obesity.
Ferulic acid	C. cryspus and U. lactuca.	Inhibits TNF-a, angiotensin-I, and PKc	Anticancer & Anti- inflammatory activity, Anti-hypertensive.
Gallic Acid	F. distichus & F. spiralis.	Inhibits ribonucleotide reductase, COX and activation of ATM kinase	Anti- Inflammatory, Anti-cancer.
Fucoxanthin	Brown seaweed.	Inhibits tumor cell growth by inducing G <sub>1</sub> cell cycle and NF-kB	Anti-inflammatory, Anti-cancer.
Phycocyanin	Red seaweed.	Inhibition of COX-2, TNF-a and histamine release	Antimicrobial and antiinflammatory.
Beta Carotene	Green Seaweed.	Regulate lipid peroxidation and decrease NF-kB p65 protein, TNF and MAPK1	Anti-Inflammatory and anticancer.
Zeaxanthin	Red Algae	Prevents LDL oxidation, inhibits Nrf-2 and binds to glutathione S-transferase.	Anti-inflammatory, and Antiproliferative.
Fucoxanthinol	Red Algae.	Inhibits CDK-4, MAPK and promotes cell cycle arrest	Anti-mutagenic, anti-diabetic, anti-obesity, Anti-inflammatory and anticancer.
Tunaxanthin	Red Fish.	Not known	Anticarcinogenic and antiinflammatory.
Phloroglucinol	Brown Algae.	Inhibits iNOS, NF-kB, IL-6, IL-1 $\beta$ and TNF-a	Antidepressant, Antiviral, Antimicrobial, Anti-tumor & Anti-inflammatory.
Violaxanthin	Chlorella ellipsoidea.	Induces NF-kB pathway	Anti-inflammatory, antiproliferative and anti-photoaging.

Epicatechin	Halimedasp., Palmaria palmata, Sargassum pallidum, Fucus vesiculosus.	Activates Nrf2, PI3K, Insulin secretion, MEF2 and Inhibits ROS, NF-kB	Anti-arthritic and anti- inflammatory, Anti-diabetic, anti-cancer and neuroprotective effect.
Fucolls	Brown Algae.	Bind to the bacterial protein and cause cell lysis, Inhibits COX-2, NF-a and NF-kB	Antibacterial, Chemoprevention against vascular risks, antiplasmin inhibition.
Phlorethols	Brown Algae.	Bind to the bacterial protein and cause cell lysis, Inhibits COX-2, NF-a and NF-kB	Antibacterial, Chemoprevention against vascular risks, antiplasmin inhibition.
Fuhalols	Brown Algae.	Bind to the bacterial protein and cause cell lysis, Inhibits COX-2, NF-a and NF-kB	Antibacterial, Chemoprevention against vascular risks, antiplasmin inhibition.
Sulphited phlorotannins	Brown Algae.	Inhibits NO production in lipopolysaccharide .	Antibacterial, Chemoprevention against vascular risks, antiplasmin inhibition.
Hyrtiloscalarane A	Hyrtilos erectus.	Inhibits COX-2 and atocopherol	Anti- inflammatory.
Hyrtiloscalarane B	Hyrtilos erectus.	Inhibits COX-2 and atocopherol	Anti- inflammatory.
Agar	Red seaweeds.	Inhibits TNF-a, PGE <sub>2</sub> , Pro inflammatory cytokines and COX-2	Antitumor agent, Anti-inflammatory.
Carrageenan	Red seaweed, Chondrus, Gigartina, Eucheuma, furcellaria sp.	Obstruction of cell cycle phase of virus	Antiviral Activity, Anti-cancer, antimicrobial, antiinflammatory and wound healing.
Alginic Acid	brown seaweeds.	Inhibit histamine release and activation of macrophages, stimulate lysosome production.	Anti- anaphylactic immunomodulatory and antiinflammatory.
Mannitol	Brown Seaweeds.	Reduces intracranial pressure. Intraocular pressure	Antibacterial, Neuroprotective.
Iodine	Saccharina japonica Ecklonia sp., Sargassum fusiforme .	Blocks Na <sup>+</sup> :I <sup>-</sup> Symporter causing ‘thyroid constipation’ .	Antibacterial Anti thyroid activity.
Fucoidan	Brown seaweeds, fucus, Ascophyllum, saccharina	Obstruction of cell cycle phase of virus .	Anti-cancer, antimicrobial, anti-inflammatory, anti-viral and wound healing.

## Structures







## 6. Challenges and future prospective

Despite their therapeutic potential, natural antioxidants face several research and application challenges. The inconsistency in antioxidant activity due to variations in extraction methods, extraction time, choice of solvent, environmental conditions, and species sources limits their standardization and reproducibility and also possess adverse effects on health [164][165]. Additionally, the lack of large-scale human trials on the long-term efficacy and safety of natural antioxidants hinders their acceptance in pharmaceutical and nutraceutical industries. These antioxidants are often suffering from low stability, bioavailability, and solubility, reducing their effectiveness in

therapeutic applications [166][167]. Factors such as pH sensitivity, oxidative degradation, and poor absorption hinder their formulation into stable drug delivery systems. Advancements in nano formulation techniques, such as nanoencapsulation, have enhanced bioavailability, minimized side effects, and safeguarded active ingredients from degradation [168][169]. With growing interest in natural health products, there is potential for developing novel antioxidant-based therapeutics for neurodegenerative diseases, cancer, and metabolic disorders. The combination of natural antioxidants with synthetic molecules or their inclusion in targeted drug delivery systems may improve their clinical efficacy. Additionally, integrating dietary antioxidants and food supplements help to reduce oxidative stress and boost energy levels in healthcare professionals experiencing work overload [31].

## 7. Conclusions

Natural antioxidants derived from natural sources play a vital role in combating oxidative stress and preventing chronic diseases. This review highlights their structural diversity, mechanisms of action, and therapeutic potential. While plant-derived antioxidants, particularly polyphenols and flavonoids, have been extensively studied, bioactive peptides from animal sources and marine antioxidants, such as astaxanthin, exhibit unique biomedical applications. Mineral-based antioxidants, including selenium and zinc, are essential for enzymatic antioxidant activity and metabolic regulation. Despite their potential, challenges such as poor bioavailability, stability issues, and formulation limitations hinder their widespread application in functional foods, pharmaceuticals, and nutraceuticals. Advancements in nano formulation techniques, such as nanoencapsulation and targeted delivery systems, offer promising solutions to enhance their efficacy, protect active ingredients from degradation, and reduce side effects. Future research should focus on optimizing delivery methods, exploring synergistic interactions between different antioxidant sources, and conducting large-scale clinical studies to validate their therapeutic benefits. A deeper understanding of these bioactive compounds will contribute significantly to the development of innovative strategies for health promotion, disease prevention, and the management of oxidative stress-related disorders.

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