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GREEN GUARDIANS: PLANT-DERIVED ANTIOXIDANTS AND THEIR ROLE IN OXIDATIVE STRESS CONTROL

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ABSTRACT

Oxidative stress develops when the body's antioxidant defenses cannot neutralize excessive production of free radicals and reactive oxygen species (ROS). Overproduction of ROS, including superoxide, hydroxyl radicals, and hydrogen peroxide, may damage cellular components, causing pathways associated with cancer, metabolic diseases, cardiovascular disease, and neurodegeneration. The positive effect of plant-derived antioxidants is the capacity to neutralize ROS-mediated damage; hence, there is increased scientific interest in this category of antioxidants. This review discusses the use of plant-based antioxidants to alleviate oxidative stress, the role of ROS in disease pathogenesis, and the opportunities/limitations of applying these natural compounds in clinical practice. Relevant literature on phytochemicals with antioxidant properties, such as polyphenols, flavonoids, terpenoids, carotenoids, and alkaloids, was analyzed. The literature on their ROS-neutralization mechanisms, biological effects, and influences on bioavailability was evaluated. New technological improvements in delivery technologies were also considered. Plant antioxidants show great promise in regulating oxidative damage by scavenging ROS, modulating redox pathways, and enhancing endogenous defence mechanisms. It has been demonstrated to be widely clinically useful across a variety of disease models. Nevertheless, their clinical performance is limited by factors like low absorption, instability during digestion, and rapid breakdown in the body. Recent delivery methods, such as nanoformulations, liposomal encapsulations, and polymer-based carriers, have the potential to enhance stability and bioavailability. Plant-derived antioxidants remain worth considering for treating ROS-induced cellular damage and preventing diseases associated with oxidative stress. Addressing existing constraints by improving the quality of delivery systems could increase their therapeutic relevance and make them applicable to evidence-based clinical practice.

Keywords: Antioxidants, Oxidative stress, Free radicals, Health benefits, Plant-derived compounds.

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1. INTRODUCTION

1.1. Cellular damage by Free Radicals and Reactive Oxygen Species

Oxidative stress occurs when the production of reactive oxygen species (ROS) exceeds the ability of the cellular antioxidant defenses, and the balance shifts in favor of cellular damage. Free radicals, which have one or more unpaired electrons, are easily associated with biological substrates in the effort to stabilize themselves (Afzal et al., 2025). Radical oxidants include superoxide (O_2-), hydroxyl radicals (OH), and non-radical oxidants, including hydrogen peroxide (H_2O_2). These molecules arise continually during normal physiological processes, particularly mitochondrial electron transport, where incomplete oxygen reduction leads to electron leakage. Additional ROS are produced through peroxisomal β-oxidation, the activity of cytochrome P450 enzymes, exposure to xenobiotics, and immune-driven oxidative bursts mediated by NADPH oxidases (Rajan, 2025).

Overproduction of ROS interferes with cellular homeostasis in a cascade of self-perpetuating reactions. Lipid membranes are highly susceptible (Liu et al., 2023), and ROS trigger lipid peroxidation, producing reactive aldehydes that can destroy neighboring lipids, proteins, and nucleic acids (Engwa et al., 2022). The proteins are oxidized, and peptide bonds are cleaved, leading to loss of enzymatic activity, deregulated signaling pathways (Halliwell, 2022), and accumulation of misfolded or aggregated proteins. ROS cause oxidative damage to DNA, such as base changes, strand breaks, and cross-linking, thereby disrupting replication fidelity and transcriptional accuracy (Dillon & Brennan, 2022). Over time, biochemical insults impair mitochondrial function, increase ROS

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generation, and initiate apoptotic cascades by releasing cytochrome c and activating caspases (Houldsworth, 2024). Together, the prolonged asymmetry between ROS and antioxidant defense triggers structural defects and functional deterioration in the cell (Sies et al., 2022). This mechanistic knowledge gives the conceptual framework of assessing the ability of plant-derived antioxidants to reverse oxidative damage by neutralizing free radicals (Sadiq, 2023), stabilizing cellular membranes, and endogenous defense mechanisms (Chandimali et al., 2025).

1.2. Importance of Antioxidants in Maintaining Redox Homeostasis

Antioxidants can be crucial for sustaining redox homeostasis in living systems by establishing and removing ROS. Organelles such as chloroplasts and mitochondria continuously produce ROS in plants, particularly during stress. They should have efficient antioxidant systems to prevent injuries. To achieve this, plants employ both enzymatic and non-enzymatic antioxidants (Akbari et al., 2022). They are glutathione-ascorbate system, tocopherols, carotenoids, and phenolic compounds. These compounds have the actions of scavenging free radicals, regulating redox, and chelating metal ions. In addition to inhibiting oxidative damage, antioxidants also facilitate signaling mechanisms that enable plants to adapt to stress (Chen et al., 2024). To maintain redox homeostasis, antioxidant systems also keep essential cellular processes, such as mitochondrial activity, metabolic signaling, and protein folding, intact, which depend on a stable redox environment (Spinelli et al., 2025). Redox imbalance can cause oxidative stress, a condition associated with most chronic diseases, such as cardiovascular, neurodegenerative, and metabolic disorders, when antioxidant defense mechanisms are inadequate or overloaded (e.g., through excess ROS production or disruption of metal-ion homeostasis) (McBeth et al., 2025).

1.3. Plants - Rich Sources of Natural Antioxidants

Antioxidants are naturally available in plants. They produce numerous antioxidant substances that help maintain internal harmony and protect against oxidative stress. ROS production increases under biotic or abiotic stress. This provokes plants to produce more antioxidants such as vitamins C and E, phenolic acids, and tannins (Mucha et al., 2021). These substances are used as reducing agents and metal chelators, helping neutralize free radicals and eliminate oxidative damage. Various plants/fruits are rich in antioxidants, and therefore many are considered useful natural sources of antioxidants that are commonly studied in relation to their health benefits (Cui et al., 2020). Eating a wide range of plant-based foods provides a variety of antioxidants that help maintain redox balance and overall health. Plants in this manner, can be considered as a natural and readily available source of antioxidants to supplement the natural body defense mechanisms (Alara et al., 2023; Godlewska et al., 2023).

2. Sources of Plant-Derived Antioxidants

2.1. Fruits

Fruits are also rich in carotenoids and flavonoids, among other antioxidants that are important in health. Tomatoes, goji berries, and apricots are especially rich in carotenoids that are responsible for their bright coloring and nutritional value. Flavonoids are also present in numerous fruits (e.g. berries, grapes, citrus varieties, etc.), mostly in the skins of fruits and the seeds (Table 1). These compounds play an important role in preventing oxidative stress and related diseases in the body (Zhang et al., 2021).

Table 1: Flavonoids reported in various parts of different fruits

Fruits	Botanical Name	Flavonoid-containing part	Flavonoids	References
Citrus fruits	*Citrus limon*	Peels of citrus fruits	Polymethoxyflavone	Saini et al. (2022)
Blueberries	*Vaccinium corymbosum*	Flowers, fronds, and leaves	Anthocyanins	Rossi et al. (2022)
Bananas	*Musa*	Leaves and stems	Catechins	Patil et al. (2022)
Apples	*Malus domestica*	Nuts, flowers, and stems	Quercetin	Baqer et al. (2024)
Peaches	*Prunus persica*	Leaves, fruits, flowers, roots, and vegetables	Kaempferol	Li et al. (2025)
Pears	*Pyrus*	Fruits and seeds	Proanthocyanidins	Su et al. (2025)
Red grapes	*Vitis vinifera*	Leaves, fruit, and bark	Epicatechins	Carpentieri et al. (2023)
Strawberries	*Fragaria ananassa*	Flowers, fronds, and leaves	Anthocyanins	Rossi et al. (2022)
Cranberries	*Vaccinium subg.oxyccus*	Leaves, flowers, and barks	Quercetin-3-galactoside	Šedbarė et al. (2023)
Blackberries	*Rubus fruticosus*	Fruits, stem, and roots	Cyanidin-3-glucoside	Lee et al. (2024)

2.2. Vegetables

Vegetables are among the most crucial food sources of antioxidants and essential nutrients (Fig. 1). The water-soluble and fat-soluble antioxidants, essential minerals, and vitamins found in carrots help improve immune function and provide anticancer effects (Salehi et al., 2020). The pumpkins are also handy because of their high

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concentration of carotenoids, vitamins, and minerals, which are generally beneficial for health. Spinach contains high amounts of carotenoids and minerals, which help prevent oxidative damage. Potatoes also contain high amounts of starch, fiber, flavonoids, and alkaloids, which help prevent disease and maintain a healthy digestive system (Naseer et al., 2019).

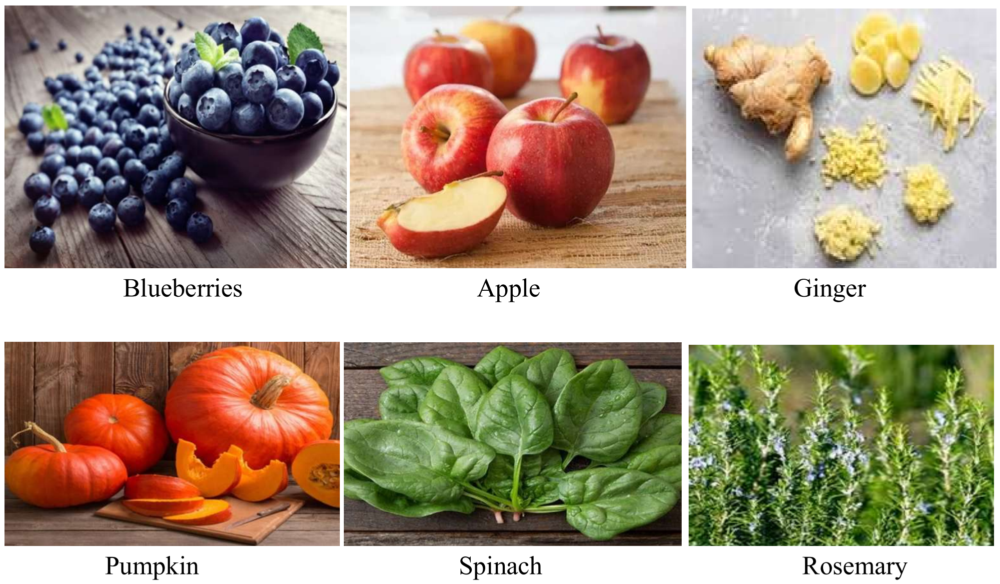

Fig. 1: Antioxidant-rich plant foods.

2.3. Herbs and Spices

The advantages of herbs and spices are numerous and include antioxidant, antimicrobial, and anti-inflammatory effects (Table 2). The leaves of the plant are the herbs and the leaves, roots, bark, or stems are the spices. One such product of Camellia sinensis can be green tea. It also contains antioxidant compounds (catechins) that increase enzyme activity and reduce oxidative damage (Michalak, 2022). Rosemary is another powerful source of antioxidants and this is a commonly employed natural preservation in the food industry. It contains active components such as rosmarinic acid and carnosic acid, which help protect cells against membrane disruption and oxidative stress (Kammath et al., 2021).

Table 2: Herbs and spices as sources of plant-derived antioxidants

Spices	Bioactive compounds	Beneficial effects	Sources
Cinnamon	Cinnamaldehyde	Antioxidant	Suryanti et al. (2018)
Ginger	Gingerol	Antioxidant	Mao et al. (2019)
Turmeric	Curcumin	Anti-inflammatory	Razavi et al. (2021)
Onion	Flavonoids	Antioxidant	Sagar et al. (2020)
Red pepper	Curcumin	Anti-inflammatory	Srinivasan, (2022)
Clove	Eugenol	Antioxidant	Alieozaman et al. (2024)
Oregano	Carvacrol	Anti-microbial	Grigore-Gurgu et al. (2025)
Thyme	Thymol	Anti-inflammatory	Marc et al. (2022)

3. Types of Plant Antioxidants

3.1. Phenolic Acids

Phenolic acids form one of the most common classes of secondary metabolites that are found in large quantities in cereal grains and other vegetable foods. Phenolic acids have an important role in controlling the color, taste, and antioxidant capability of plants (Preedy, 2020). Natural antioxidants, such as ferulic acid and caffeic acid, are protective against ultraviolet light, microbial infections, and pests. The hydroxyl groups in aromatic rings make them antioxidants; they can donate a hydrogen atom, quench singlet oxygen, and scavenge reactive oxygen species (Yang et al., 2020). Phenolic acids are essential for protecting cellular components such as lipids, proteins, and DNA from oxidative damage. These are very common in fruits, vegetables, whole grains, and seeds and make a significant contribution to the antioxidant effect of a plant-based diet (Shakya et al., 2024). Phenolic acids such as

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caffeic acid, ferulic acid, and gallic acid are common in that they are potent radical-scavenging and metal-chelating agents (Deka et al., 2022).

3.2. Flavonoids

The other notable group of antioxidants in plants are the flavonoids, which are prevalent in the plant kingdom. These are compounds that are rich in antioxidant and therapeutic properties and are therefore used in prevention of diseases that take long duration such as cardiovascular diseases, cancer and neurodegenerative diseases (Stasiłowicz-Krzemień et al., 2024). The flavonoids have been grouped into subgroups such as flavones, isoflavones and flavonols which possess distinct structural and functional properties. Flavonoids play two roles in plants which include, protecting the plants against environmental stressors like UV and pathogens and as attractants of pollinators, to enable reproduction and seed dispersal (Pereira et al, 2025). In addition to their antioxidant activity, flavonoids promote anti-inflammatory processes and help stabilize cellular signaling networks. They contain lots of fruits, leafy vegetables, tea, cocoa, and numerous medicinal plants and thus form a significant part of a diet that is taken to keep the overall health (Behl et al., 2022; Akbari et al., 2022).

3.3. Phenolic Compounds

The two major subclasses of phenolic compounds are lignans and stilbenes, which possess varying biological activity. Lignans are polyphenolic substances found in food and feed that have estrogen-like, anti-inflammatory, and antioxidant effects, supporting general health and well-being. High-dietary sources of lignans, such as flaxseeds, vegetables, and fruits, are typically recommended for their health-protective properties (Mohapatra et al., 2024). Stilbenes, however, are significantly involved in plant defense systems and are only found in a few sources of diet such as berries, peanuts, grapes, and red wine. Among them, resveratrol is the most comprehensive in its range of health benefits, including the potential to improve cardiovascular health, blood sugar levels, and to prevent age-related issues (Arrigoni et al., 2023).

3.4. Tannins

Tannins are a chemically heterogeneous group of plant polyphenols that were initially used to tan leather, hence the name. These are typically divided into two categories: hydrolysable and non-hydrolysable tannins and have relatively high molecular weights (Moon, 2024). They have antioxidant activity due to their strong electron-donating ability, which helps stabilize free radicals and prevent oxidative stress. Their high molecular weight and presence of several hydroxyl groups in tannins also contribute to their ability to act as good free radical scavengers (Gulcin, 2020). Tannins are also important in plant defense, as they deter herbivores and prevent the growth of destructive microorganisms. In addition to their occurrence in plants, they are used in food and pharmaceutical industries, including food preservation, nutraceutical and anti-inflammatory or antimicrobial development (Pereira et al., 2025). Also, the tannin substance may react with digestive enzymes and proteins in the gut, which can affect nutrient absorption and could have therapeutic effects in the case of metabolic disorders. They are versatile both biologically and industrially, and thus the topic of current research in natural product chemistry and pharmacology (Rajan, 2025). Tannins are phenolic compounds naturally present in several plants and are part of plant antioxidants (Fig. 2). They play a variety of biological functions, including antioxidant activity, antimicrobial activity, and protection against oxidative stress.

3.5. Vitamins

One of the vitamins is Vitamin A, a lipophilic molecule commonly referred to as retinoic acid, which is an antioxidant. Monaghan and Schmitt were the first to prove the antioxidant activity of Vitamin A. Over 600 carotenoids have been identified so far. Vitamin A inhibits lipid peroxidation by reacting with peroxyl radicals, and retinoic acid was found to increase the expression of genes encoding intrinsic antioxidant enzymes. Furthermore, retinol activates antioxidant enzymes, such as glutathione transferase and superoxide dismutase, suggesting that Vitamin A may be a potent endogenous antioxidant (Milisav et al., 2019). Vitamin C (ascorbic acid) is a water-soluble antioxidant, which is found in most fruits and vegetables, and is essential in neutralizing the free radicals and cell oxidation. It is also capable of suppressing lipid peroxidation and is a vital defense molecule in the body (Park et al., 2022). The other fat-soluble antioxidant, vitamin E, is concentrated in the cell membrane, helping prevent the formation and accumulation of free radicals and, consequently, oxidative damage. The body's antioxidant system is a significant component of this vitamin combination, ensuring cellular integrity and protecting against oxidative stress-related disorders (Alawad et al., 2024).

Another significant category of plant antioxidants is vitamins, which are fat-soluble vitamin A and E and water-soluble vitamin C and which have vital roles in eliminating the free radicals and cellular integrity (Fig. 2). They not only scavenge reactive oxygen species directly but also regulate the gene expression of antioxidant enzymes and inflammation (Ayaz et al., 2024). Besides acting as direct antioxidants, vitamins like A, C, and E tend

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to act in synergy, where each is regenerated by the others to increase overall cellular protection against oxidation. Other effects of these vitamins include modulation of gene expression, inflammation, apoptosis, and immune response signaling pathways, which also contribute to their protective effect (Cui et al., 2020). Also, they are essential in terms of the structural integrity of the tissues, vision, skin and cardiovascular performance. Their consumption rate, thus, plays a critical role in neutralizing the free radicals and ensuring long-term cellular and system health (Akbari et al., 2022).

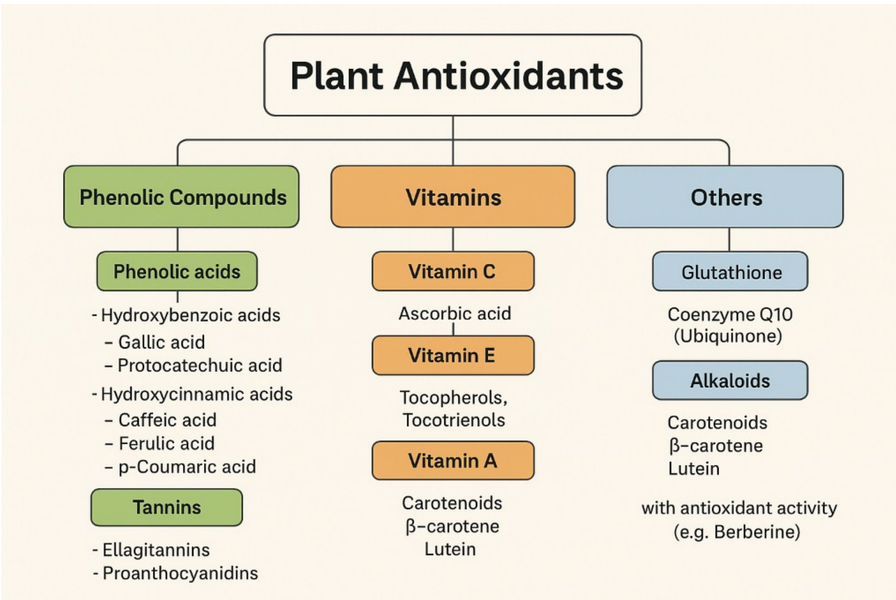

Fig. 2: Types of different antioxidants found in plants.

3.6. Plant Pigments

The other major group of antioxidants are plant pigments which possess the property of neutralizing the free radicals and reactive oxygen species. Chlorophylls, carotenoids and anthocyanins are the most important pigments. Although the primary role of chlorophylls is to capture light energy during photosynthesis, carotenoids and anthocyanins enable plants to be intensely colored and protect cells against oxidative damage (Dumanović et al., 2021). Carotenoids that impart yellow, orange, and red coloration to plants are especially efficient at quenching singlet oxygen and free radicals because of their distinctive polyene structures. They are rich in deep-colored fruits and vegetables like carrots, papayas, spinach, apricots, beetroots, and sweet potatoes and thus form a crucial part of a healthy diet and natural antioxidant protection (Young & Lowe, 2018). Fig. 2 in vitamins and other antioxidants also shows plant pigments, including carotenoids and anthocyanins, which have a high free radical-quenching capacity. Besides the antioxidant effect, plant pigments like carotenoids and anthocyanins have been found to control cellular signaling mechanisms and inflammation and oxidative stress gene expression (Michalak, 2022). Anthocyanins, anthocyanins, which give fruit and vegetable products their red, purple, and blue color, have high metal-chelating and free radical-scavenging properties too (Pereira et al., 2025). Not only are these pigments beneficial to the health of plants, but they also have great health advantages to humans, such as protection against cardiovascular diseases, some types of cancer, and degenerative age-related diseases and disorders. The frequent intake of fruits and vegetables rich in pigments is thus necessary to supplement the endogenous antioxidant defense system in the body (Rajan, 2025).

4. Mechanisms of Action of Antioxidants

4.1. Free Radical Scavenging

When oxygen is consumed in the process of normal cellular respiration, mitochondria produce free radicals as by-products. ROS and reactive nitrogen species (RNS) are highly reactive molecules produced by this process (Alzahrani, 2021). Free radicals easily engage with nearby biomolecules and are themselves less stable compared to non-radical species. When two radicals collide, they can form a covalent bond by sharing their unpaired electrons and stabilizing each other. But in living organisms, most molecules are non-radical in character, and radicals either donate or accept an electron to become stabilized, frequently resulting in the production of new radicals (Hanafy & Hill, 2021). During the antioxidant process, antioxidants neutralize reactive oxygen species

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that steal electrons or hydrogen atoms, thereby stabilizing free radicals and inhibiting their ability to damage vital cellular molecules such as lipids, proteins, and DNA (Kalaskar & Patil, 2025). This not only protects structural molecules but also maintains normal functioning of enzymes and signaling pathways. Antioxidants are important for maintaining redox homeostasis in cells by continuously intercepting and stabilizing reactive species (Vishwakarma et al., 2025).

4.2. Metal Ion Chelation

Metals like mercury, iron, copper, and zinc are essential in numerous biological processes such as enzyme function, cell development, and the immune response. The metals, though, can catalyze the formation of free radicals and ROS when in excess, causing oxidative damage and tissue injury (Santos et al., 2022). Accumulation of heavy metals may have severe effects to vital organs such as the digestive system, nervous system and reproductive system. Metal chelation refers to the integration of the creation of a ring-shaped complex between a metal ion and a ligand to allow the excretion of poisonous metals out of the body in a safe way (Gulcin & Alwasel, 2022). Where trace metal essentiality is a condition for optimal enzyme function, excessive accumulation promotes oxidative stress by increasing ROS and RNS production and can oxidize lipids, proteins, and nucleic acids (Malacaria et al., 2022). Natural chelating agents, such as phenolics and flavonoids, are preferable to synthetic agents because they offer similar efficacy with fewer chances of toxicity. Antioxidants stabilize complexes with these metals and, through this mechanism, inhibit their involvement in reactions like the Fenton reaction that creates harmful hydroxyl radicals (Michalak, 2022). This chelation mechanism prevents the oxidative damage of cellular components such as lipid, protein and DNA (Zhu et al., 2024). Moreover, metal-binding antioxidants help preserve overall redox status and maintain regular cellular activity by reducing metal-induced oxidative stress (Parveen et al., 2025).

4.3. Inhibition of Lipid Peroxidation

One of the most common forms of oxidative damage of biological systems is lipid peroxidation. Lipids are readily attacked by ROS and free radicals, generating secondary products known as lipid peroxidation (LP) products, which serve as indicators of oxidative stress (Zhang et al., 2021). These LP substances are not just indicators of oxidative damage but also propagators of oxidative damage as they react with proteins and other biomolecules thereby enhancing cellular damage. Plant antioxidants prevent peroxidative chain reactions by scavenging radicals and stabilizing lipid membranes, thereby preserving cell integrity (Yang et al., 2023). Antioxidants prevent the oxidation of cell membranes by inhibiting lipid peroxidation which is a vital process. In lipid peroxidation, the polyunsaturated fatty acids of the membrane are attacked by the reactive oxygen species to form lipid radicals, which spread chain reactions and break the integrity of the membrane (Valgimigli, 2023). These antioxidants come in and neutralize these lipid radicals as well as ending the chain reaction and thus preventing further oxidative damage. This defense mechanism maintains membrane integrity, preserves normal cellular activity, and contributes to redox balance throughout the body (Zhang et al., 2024).

4.4. Regulation of Antioxidant Enzymes (SOD, CAT, GPx)

A series of antioxidant enzymes collaborates in defense against oxidative damage to cells. Superoxide dismutase (SOD) breaks down the superoxide radicals into hydrogen peroxide and oxygen with the assistance of copper, zinc, manganese, and iron. This is then done by Catalase (CAT), which decomposes hydrogen peroxide to water and oxygen. Another antioxidant defense mechanism is glutathione peroxidase (GPx), which breaks down lipid hydroperoxides and removes excess hydrogen peroxide (Manessis et al., 2020). These enzymes work together to ensure redox homeostasis and prevent redox-mediated injury to cellular macromolecules (Mihailović et al., 2021). SOD converts superoxide radicals into hydrogen peroxide, and this reactive oxygen species is neutralized by CAT and GPx (Rao et al., 2025). Antioxidants can ensure effective ROS detoxification by increasing the activity of enzymes or inhibiting their inhibitors, thereby minimizing oxidative stress on cellular components. The overall health of the cell and redox homeostasis result from the concerted action of enzymatic defenses (Akbari et al., 2022). Fig. 3 shows the mechanism of SOD, GPx, and lipid peroxidation:

5. Health Benefits of Plant Antioxidants

5.1. Cardiovascular Protection

Polyphenols have received considerable attention as potential beneficial agents for cardiovascular health, as they can mitigate the effects of oxidative stress and enhance endothelial function (Shah et al., 2019). Polyphenols contribute to vascular health by increasing nitric oxide production, which regulates blood vessel dilation and tone (Rolnik et al., 2020). It has been established that an oral intervention of red wine polyphenolic compounds can inhibit the lipid deposition, inflammation and neointimal growth of arterial walls by predominantly anti-inflammatory mechanisms. Their effect involves inhibiting the oxidation of low-density lipoprotein (LDL) cholesterol, a significant contributor to the development of atherosclerotic plaques and to healthy arteries (Aguayo-Morales et al., 2024). These compounds also play a role in the sustenance of the elasticity and the structural integrity of the blood vessels that play a role in the normal blood flow and the blood pressure regulation. The presence of plant antioxidants may also be useful due to improving the endothelial functionality and lowering the state of inflammation that may ultimately decrease the risk of heart disease and create long-term cardiovascular wellbeing (Khoso et al., 2025).

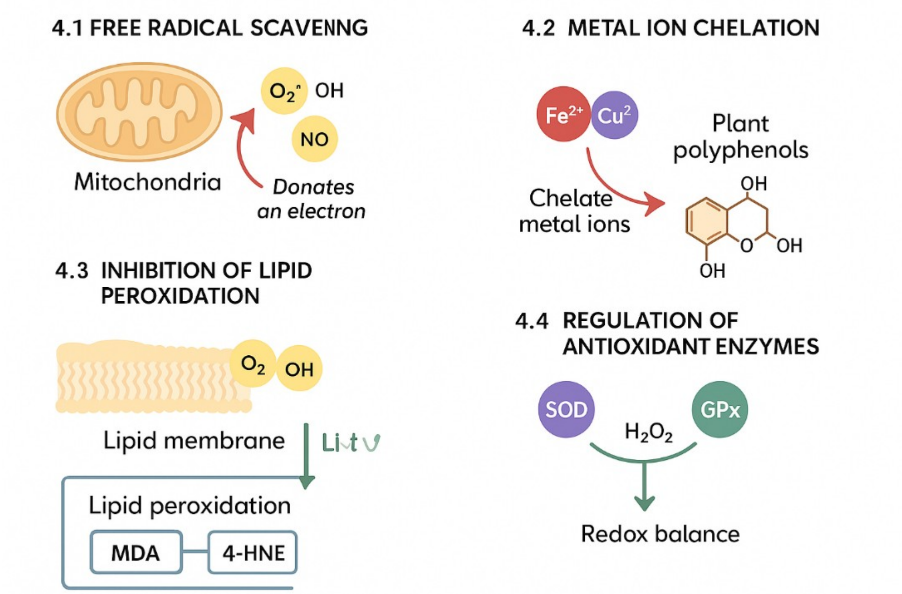

Fig. 3: Mode of action of the antioxidant enzyme system.

5.2. Neuroprotection

The antioxidant properties of fruits, particularly berries, have been found to improve cognitive processes, such as memory and learning. It is not only that these have antioxidant activity but also that they can be used to reduce blood pressure, prevent neuroinflammation, reduce cardiovascular risk, regulate glucose metabolism, and increase hippocampal neurogenesis (Hussain et al., 2018). Cherry juice is reported to promote verbal fluency, memory, and visual attention in older adults over the long term. Vegetables such as onions, which are rich in quercetin, have been shown to prevent cognitive impairment among the elderly. Similarly, cocoa, one of the most flavonoid-rich foods, enhances neurogenesis and neuroplasticity by stimulating the production of brain-derived neurotrophic factor (BDNF) and improving neurovascular performance (Miller et al., 2018). They preserve neuron structure and functionality, which contribute to preserving cognitive functions and potentially reducing the risk of neurodegenerative and related disorders, including Alzheimer's and Parkinson's diseases (Jarne-Ferrer et al., 2025). These antioxidants also disrupt inflammatory pathways and support mitochondrial activity, both of which promote neural health. Regular consumption of plant foods rich in antioxidants can thus contribute to the long-term resilience of the brain and the nervous system more broadly (Shoaib et al., 2023).

5.3. Anti-Cancer Properties

There is a growing acceptance of herbal drugs as safe, viable and effective sources of bioactive compounds having anticancer action. It is their phytochemicals that counter oxidative injury in relation to disease and prevent tumor growth. Most indigenous medicinal plants such as Phaleria macrocarpa and Fagonia indica are used as cancer preventives (Ijaz et al., 2018). Plant derived extracts have metabolites capable of causing cancer cell apoptosis. Gallic acid is another bioactive compound of P. macrocarpa that exhibits high apoptotic effects on a variety of cancer cell lines, like lung, leukemia, and colon adenocarcinoma (Shrihastini et al., 2021). They interfere with the cell signaling pathways, stimulating programmed cell death (apoptosis), of abnormal or precancerous cells and suppressing unregulated cell division (Hashim et al., 2024). Moreover, these antioxidants decrease chronic inflammation and restrain the creation of carcinogenic substances, which makes the environment less conducive to the growth of tumors. Frequent eating of plant foods rich in antioxidants could thus reduce the risk of cancer as well as contribute to the proper health of cells in general (Zhao et al., 2023).

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5.4. Anti-Aging Effects

Antioxidants play an equally important role in ensuring skin health and preventing aging-related deterioration. Vitamin C guards the skin against photooxidative damage and promotes collagen production, while vitamin E enhances the elasticity of skin and prevents wrinkle formation. Fruits, vegetables, and other phytofoods high in these antioxidants boost the skin's built-in photoprotective functions and enhance cellular regeneration (Arangia et al., 2023). Proline, lysine, and vitamin C are used to make collagen, which ensures skin firmness and elasticity. Collagen peptide supplementation has been found to increase skin hydration and elasticity, particularly among older individuals (Nobile et al., 2023). Moreover, antioxidants counter the effect of reactive oxygen species (ROS) produced by UV rays, pollution, and metabolism, which are the primary causes of early skin aging (Michalak, 2022).

Plant-derived flavonoids and polyphenols lower the expression of matrix metalloproteinases (MMPs), which break down collagen and elastin, restraining the development of wrinkles and skin sagging (Das et al., 2024). Another effective antioxidant, coenzyme Q10, aids mitochondrial activity in skin cells, which produce energy and support cellular repair. Antioxidants also stabilize cell membranes and inhibit lipid peroxidation, thereby preventing oxidative damage to skin lipids that retain moisture and barrier function (Salehi et al., 2020). Topical epidermal regeneration and reduction in epidermal inflammation have been reported with antioxidants such as resveratrol and green tea catechins. In addition, diets high in antioxidants alter the inflammatory signaling pathway and reduce chronic low-grade inflammation, thereby increasing the rate of skin aging (Cui et al., 2020). Lifestyle beliefs, such as frequent intake of antioxidant-rich foods and sun protection, synergize to increase the skin's resistance to environmental factors. All these measures help to sustain structural integrity of the skin, slow the appearance of aging, and overall skin activity (Alawad et al., 2024). Fig. 4 represents the positive health outcomes of aging, cancer, microbial and others properties:

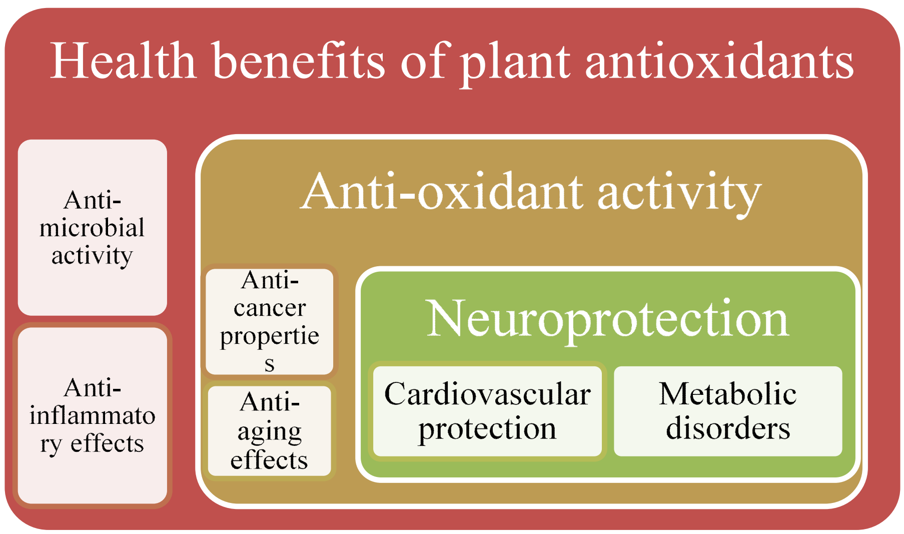

Fig. 4: Health benefits of plant antioxidants.

6. Applications in Food and Medicine

6.1. Use in Nutraceuticals and Functional Foods

Proper nutrition is a key to ensuring general health and well-being, and the world food industry also focuses more on creating products that help achieve this end. Functional foods and nutraceuticals have become innovative solutions to enhancing public health as well as lowering healthcare costs (Di Sotto et al., 2020). Functional foods incorporate bioactive compounds that not only serve fundamental nutritional functions but also deliver physiological value, preventing or managing several lifestyle-associated disorders. A food is said to be functional if it provides health benefits over and above its intrinsic nutrients (Shang et al., 2021).

Nutraceuticals, however, are foods with bioactive ingredients that have therapeutic benefits. These ingredients may be isolated and purified from plants, animals, or sea organisms and are commonly used to favorably influence the prevention or treatment of diseases. The rising use of such products has contributed towards an expanding international market and debate regarding their categorization since they blur the conventional lines between diet and medicine (Saleem et al., 2021). Examples include fortified foods, such as dairy products (e.g., milk with casein as its functional nutrient), and fruits like oranges that supply ascorbic acid as a health-promoting factor. Hence, nutraceuticals fill the gap between pharmacology and nutrition as they supply natural and preventive medicine for health maintenance and disease control (Kataki et al., 2019).

Some of the most commonly used bioactive plant compounds in functional foods and nutraceutical preparations include polyphenols, flavonoids, carotenoids, vitamins, and fibers, owing to their antioxidant, anti-inflammatory, cardioprotective, and metabolic regulatory effects (Engwa et al., 2022). Various Natural phenolic sources are used in foods due to their immense antioxidant properties (Table 3). As an illustration, flaxseed oil and fish oil contain omega-3 fatty acids, which are known to support heart and brain health. In contrast, curcumin, found in turmeric, has strong anti-inflammatory and antioxidant properties (Kalaskar & Patil, 2025). Nutraceutical supplements have fruits and vegetables with a high content of anthocyanins and catechins, including berries and green tea that can be used to treat oxidative stress and inflammation, as well as reduce the risk of chronic diseases such as cancer and cardiovascular diseases (Wang & Kong, 2025). Functional foods are those that are naturally high in beneficial compounds (e.g., vitamin C-containing citrus fruits and fibers) or those with added bioactive compounds (e.g., probiotics in yogurt or vitamin-fortified cereals) that positively contribute to physiological processes and help prevent diseases (Asgary et al., 2018).

Table 3: Natural phenolic sources and their application as antioxidants as food matrix

Natural source	Main compound	Food matrix	Reference
Olive leaf	Phenolic compounds	Antioxidant film	Zhang et al. (2021)
Green tea extract	Polyphenols	Sunflower oil	Pereira et al. (2025)
Cloves and cinnamon	Phenolic compounds	Meat samples	Petcu et al. (2023)
Rosemary extracts	Phenolic compounds	Chia oil oxidation	Wang et al. (2018)
Potato peels	Phenolic compounds	Ground beef patties	Vescovo et al. (2025)
Fruits and plants	Phenolic compounds	Meat, poultry products	Manessis et al. (2020)
Apple peel	Phenolic compounds	Tomato juice	Sarkar et al. (2022)

The nutraceutical industry has been growing fast because of the increase in consumer awareness to diet-related health conditions, inactive lifestyles, and the need to consume healthier food varieties that could benefit them against diabetes, obesity, and heart diseases (Vlaicu et al., 2023). The study of formulation methods, including the encapsulation of plant antioxidants with edible polysaccharides to enhance stability, bioavailability, and directed delivery of nutraceuticals, to stimulate enhanced functional activity in humans, is still under research (Rajan, 2025). Nevertheless, the issues of fluctuating bioavailability, regulatory definition, and quality control also should not be disregarded because of the necessity to introduce the scientific validation vigorously (Pereira et al., 2025).

6.2. Role in Pharmaceuticals and Traditional Medicines

Plant antioxidants have been the focus of significant attention in both conventional medicine and pharmaceutical research for their potential to prevent and treat oxidative stress–associated diseases (Xiao & Bai, 2019). Antioxidant phytochemicals protect biomolecules such as DNA, lipids, and proteins by oxidative damage, thereby promoting the prevention of diseases and cellular homeostasis. These compounds also modify the major biological processes, including apoptosis, gene expression, and signal transduction, essential to maintain physiological balance (Rathor, 2021).

The medicinal plants that had been used traditionally have been scientifically shown to have antioxidants, anti-inflammatory and cytoprotective properties in the majority of cases. Such findings have inspired the addition of them to modern therapeutic products and pharmaceutical development (Kim et al., 2023). Food and medicinal plant-based natural antioxidants are also finding application in pharmaceuticals, nutraceuticals, and cosmetics since they are biocompatible, stable, and non-toxic (Mittal & Sharma, 2024).

7. Limitations and Challenges of Plant Antioxidants

Despite their large therapeutic potential, plant antioxidants are to be affected by several drawbacks which restrict their widespread application. Their low bioavailability, rapid metabolic breakdown, and instability under physiological conditions are among the limitations, reducing the efficacy of such drugs in vivo (Aryal et al., 2022). In addition, no standard protocols exist regarding the extraction, purification, and testing of the research, which results in a disparity of antioxidant activity in studies, making the control of the quality of the product and its clinical effectiveness challenging (Koo et al., 2018).

Excessive use of antioxidants can disrupt the redox balance within cells, potentially leading to pro-oxidant effects and even toxicity rather than protection (Pirtskhalava et al., 2024). Therefore, there is the necessity to address these problems with the help of improved bioavailability, formulation technologies, and unified protocols for helping to develop the safe and effective use of plant antioxidants in pharmaceuticals and traditional medicine (Nasim et al., 2022).

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In addition to pharmacokinetic issues, the chemical instability of many antioxidants under physiological conditions affected by pH, light, and heat further reduces their activity and complicates formulation and storage (Manessis et al., 2020). The heterogeneity of plant extracts also presents significant obstacles. Variability in species, geographical origin, harvest time, and extraction methods leads to inconsistent phytochemical composition and antioxidant activity, making standardization difficult and hindering reproducibility across studies and commercial products (Hoang et al., 2021).

Moreover, the lack of standardized dosages and well-defined dose-response relationships in clinical settings makes it challenging to determine safe and effective intake levels, potentially leading to subtherapeutic or even adverse effects (Gulcin, 2020). Excessive antioxidant use can paradoxically disturb cellular redox balance and induce pro-oxidant effects or toxicity rather than protection (Bibi Sadeer et al., 2020). To address these issues, improved delivery systems (e.g., nanoencapsulation), unified extraction and testing protocols, and rigorous clinical trials are essential, enabling reliable, safe, and efficacious use of plant antioxidants in health and food applications (Al-Madhagi and Masoud, 2024).

8. Future Perspectives

The future prospects of plant antioxidants in medicine and health are that they will go beyond the prevailing challenges by scientific and technological progress. Nanoparticles, liposomes, and polymeric carriers are nanotechnology-based delivery systems that have demonstrated significant potential to enhance stability, absorption, and targeted delivery of natural antioxidants (Rasool et al., 2021). Similarly, new technologies such as metabolomics and bioinformatics are being applied to identify new antioxidant compounds and the molecular mechanisms by which these compounds operate. The research should be directed towards future investigations that would need to optimize the extraction procedures, match dosages to evidence-based practices, and conduct clinical validation studies to ensure consistent effectiveness and safety (Thilagavathi et al, 2023). Antioxidants derived by plants are expected to be in the forefront of the next generation of nutraceutical, preventive pharmaceutical and eco-friendly drugs due to the close interdisciplinarity and development of formulation science (Khare et al., 2024).

9. CONCLUSION

Plant-derived antioxidant molecules are powerful natural agents for preventing oxidative stress in the human body and maintaining health. The prevention of various chronic diseases, including cardiovascular disease, cancer, neurodegenerative diseases, and age-related damage, is attributed to bioactive phytoantioxidants. The complexity of antioxidant molecules in plants indicates their importance as a natural protection mechanism as well as a prime ingredient of diet-based prevention and drug discovery. Even though they have some disadvantages, diet-based approaches, such as low bioavailability and standardization, should be continuously improved through extraction, formulation, and nanotechnology to optimize their clinical and nutritional applications. Overall, integrating antioxidant-rich plant foods and extracts into daily food consumption and medical practice is a promising approach to achieving better health outcomes and reducing the burden of oxidative stress-related diseases worldwide.

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