IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 13, May 2026
Impact Factor: 8.2

Role of Antioxidants in Disease: A Review

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Abstract: *Antioxidants are molecules capable of inhibiting or delaying the oxidation of other molecules by neutralizing free radicals and reactive oxygen species (ROS). Oxidative stress caused by excessive production of ROS has been implicated in the pathogenesis of numerous diseases, including cardiovascular disorders, cancer, diabetes mellitus, neurodegenerative diseases, inflammatory conditions, and aging. Antioxidants derived from endogenous and exogenous sources play a crucial role in maintaining cellular homeostasis and protecting biological systems from oxidative damage. Natural antioxidants such as vitamins, polyphenols, flavonoids, carotenoids, and enzymatic antioxidants contribute significantly to disease prevention and health promotion. This review discusses the mechanisms of oxidative stress, classification of antioxidants, sources of antioxidants, and their therapeutic role in various diseases. The paper also highlights recent advances in antioxidant research and future prospects in antioxidant therapy.*

Keywords: Antioxidants, Oxidative stress, Free radicals, Reactive oxygen species, Disease prevention, Natural antioxidants

I. INTRODUCTION

Living organisms continuously produce reactive oxygen species (ROS) and reactive nitrogen species (RNS) during normal metabolic processes. Under physiological conditions, these reactive species are balanced by endogenous antioxidant defense systems. However, excessive ROS generation or inadequate antioxidant defense results in oxidative stress, which damages cellular components including lipids, proteins, and DNA [1].

Oxidative stress has emerged as a major contributor to the development of chronic diseases such as cancer, cardiovascular diseases, diabetes, neurodegenerative disorders, and inflammatory conditions [2]. Antioxidants neutralize free radicals by donating electrons and thereby reduce oxidative damage [3].

Antioxidants may be endogenous, produced naturally within the body, or exogenous, obtained from dietary sources. Fruits, vegetables, cereals, medicinal plants, and beverages such as tea and coffee are rich sources of antioxidants [4]. Increasing scientific evidence indicates that antioxidant-rich diets can reduce disease risk and improve overall health [5].

This review aims to summarize the role of antioxidants in disease prevention and management, focusing on mechanisms, classification, sources, and therapeutic applications.

II. OXIDATIVE STRESS AND FREE RADICALS

2.1 Free Radicals

Free radicals are highly reactive atoms or molecules containing one or more unpaired electrons. Common free radicals include superoxide anion (O_2^-), hydroxyl radical (OH•), nitric oxide (NO•), and hydrogen peroxide (H_2O_2) [6].

These radicals are generated through:

- Mitochondrial respiration
- Inflammation
- Radiation exposure
- Environmental pollutants
- Smoking

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- Heavy metals
- Certain drugs

Although free radicals participate in cellular signaling and immune defense, uncontrolled production can be harmful [7].

2.2 Oxidative Stress

Oxidative stress occurs when the balance between oxidants and antioxidants is disturbed in favor of oxidants [8]. Excess ROS can cause:

- Lipid peroxidation
- Protein oxidation
- DNA mutations
- Cellular dysfunction
- Apoptosis

Oxidative stress contributes significantly to aging and disease progression [9].

III. CLASSIFICATION OF ANTIOXIDANTS

Antioxidants are classified into enzymatic and non-enzymatic antioxidants.

3.1 Enzymatic Antioxidants

These enzymes catalytically remove ROS from cells.

3.1.1 Superoxide Dismutase (SOD)

SOD converts superoxide radicals into hydrogen peroxide and oxygen [10].

3.1.2 Catalase

Catalase converts hydrogen peroxide into water and oxygen, preventing hydroxyl radical formation [11].

3.1.3 Glutathione Peroxidase

This enzyme reduces hydrogen peroxide and lipid peroxides using glutathione [12].

3.2 Non-Enzymatic Antioxidants

These include vitamins, minerals, and phytochemicals.

3.2.1 Vitamin C

Vitamin C is a water-soluble antioxidant that scavenges free radicals and regenerates vitamin E [13].

3.2.2 Vitamin E

Vitamin E protects membrane lipids from peroxidation [14].

3.2.3 Carotenoids

Beta-carotene, lycopene, and lutein protect tissues against oxidative damage [15].

3.2.4 Polyphenols and Flavonoids

Polyphenols exhibit strong antioxidant and anti-inflammatory properties [16].

IV. SOURCES OF ANTIOXIDANTS

4.1 Natural Sources

Natural antioxidants are abundant in:

- Fruits
- Vegetables
- Nuts

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- Whole grains
- Herbs and spices

Examples include berries, spinach, turmeric, green tea, grapes, and tomatoes [17].

4.2 Synthetic Antioxidants

Synthetic antioxidants such as butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT) are commonly used in food preservation [18]. However, concerns about toxicity have encouraged interest in natural antioxidants.

V. MECHANISM OF ANTIOXIDANT ACTION

Antioxidants protect cells through various mechanisms:

- Scavenging free radicals
- Chelating metal ions
- Inhibiting oxidative enzymes
- Enhancing endogenous antioxidant systems
- Repairing oxidized biomolecules [19]

These mechanisms reduce oxidative damage and maintain cellular integrity.

VI. ROLE OF ANTIOXIDANTS IN DISEASE

6.1 Cardiovascular Diseases

Oxidative stress contributes to atherosclerosis, hypertension, and heart failure. LDL oxidation plays a major role in plaque formation [20].

Antioxidants reduce cardiovascular risk by:

- Preventing LDL oxidation
- Improving endothelial function
- Reducing inflammation
- Lowering blood pressure

Polyphenols from green tea and red grapes have shown cardioprotective effects [21].

6.2 Cancer

ROS can damage DNA and induce mutations leading to cancer development [22]. Antioxidants may prevent carcinogenesis by neutralizing ROS and enhancing immune function.

Compounds such as curcumin, resveratrol, and flavonoids exhibit anticancer activities through:

- Induction of apoptosis
- Inhibition of tumor growth
- Reduction of inflammation
- Prevention of DNA damage [23]

6.3 Diabetes Mellitus

Hyperglycemia increases ROS generation, causing oxidative damage in diabetic patients [24]. Oxidative stress contributes to diabetic complications such as neuropathy, nephropathy, and retinopathy.

Antioxidants improve glucose metabolism and reduce complications by:

- Protecting pancreatic beta cells
- Reducing lipid peroxidation
- Improving insulin sensitivity [25]

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Vitamin C, alpha-lipoic acid, and polyphenols are beneficial in diabetes management.

6.4 Neurodegenerative Diseases

The brain is highly susceptible to oxidative stress because of high oxygen consumption and lipid content [26]. Oxidative stress is associated with Alzheimer's disease, Parkinson's disease, and amyotrophic lateral sclerosis.

Antioxidants may:

- Protect neurons
- Reduce neuroinflammation
- Improve mitochondrial function
- Delay disease progression [27]

Vitamin E, coenzyme Q10, and flavonoids are widely studied neuroprotective antioxidants.

6.5 Inflammatory Diseases

ROS play an important role in chronic inflammation [28]. Excessive oxidative stress activates inflammatory pathways and cytokine production.

- Antioxidants reduce inflammation by:
- Inhibiting inflammatory mediators
- Suppressing oxidative enzymes
- Enhancing immune defense [29]

Natural antioxidants are useful in arthritis, inflammatory bowel disease, and asthma.

6.6 Aging

The free radical theory of aging suggests that accumulated oxidative damage contributes to aging [30]. Antioxidants may slow aging by reducing cellular damage and preserving mitochondrial function.

Dietary antioxidants are associated with improved longevity and healthy aging [31].

VII. ANTIOXIDANTS IN FOOD AND NUTRITION

Dietary antioxidants are important for maintaining health. Functional foods enriched with antioxidants are increasingly popular.

Examples include:

- Green tea
- Dark chocolate
- Blueberries
- Turmeric
- Citrus fruits
- Nuts [32]

Balanced diets rich in natural antioxidants are more beneficial than excessive supplementation.

VIII. CLINICAL APPLICATIONS OF ANTIOXIDANTS

Antioxidants are used clinically in:

- Nutritional supplements
- Pharmaceutical formulations
- Cosmetic products
- Functional foods

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Clinical trials have shown mixed results regarding antioxidant supplementation [33]. While moderate intake is beneficial, excessive supplementation may produce adverse effects.

IX. RECENT ADVANCES IN ANTIOXIDANT RESEARCH

Recent developments include:

- Nanotechnology-based antioxidants
- Plant-derived bioactive compounds
- Mitochondria-targeted antioxidants
- Gene therapy approaches [34]

Novel antioxidants are being investigated for improved bioavailability and therapeutic efficacy.

X. LIMITATIONS OF ANTIOXIDANT THERAPY

Despite promising effects, antioxidant therapy has limitations:

- Poor bioavailability
- Dose-related toxicity
- Drug interactions
- Inconsistent clinical outcomes [35]

Further studies are needed to determine optimal dosage and therapeutic applications.

XI. FUTURE PERSPECTIVES

Future research should focus on:

- Personalized antioxidant therapy
- Combination therapies
- Identification of novel antioxidants
- Long-term clinical trials
- Molecular mechanisms of action

Advancements in biotechnology and pharmacology may improve antioxidant-based treatment strategies [36].

XII. CONCLUSION

Antioxidants play a critical role in protecting the body against oxidative stress and disease development. Both endogenous and dietary antioxidants contribute to maintaining cellular homeostasis and preventing oxidative damage. Increasing evidence supports the beneficial role of antioxidants in cardiovascular diseases, cancer, diabetes, neurodegenerative disorders, inflammation, and aging. Natural antioxidants from fruits, vegetables, and medicinal plants are especially valuable due to their safety and health-promoting properties. Although antioxidant therapy shows great promise, further research is needed to optimize clinical applications and establish evidence-based guidelines for antioxidant use.

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