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Review Article

Antioxidants and Phytochemical Profiles in Medicinal Plants: Unraveling Molecular Mechanisms

Mohamed Said[1]*, Mohamed Mursal Ibrahim[1]

[1]Erciyes University, Graduate School of Natural and Applied Science, Department of Field Crops, Kayseri, Türkiye

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***Corresponding author:** Mohamed Said
Erciyes University, Graduate School of Natural and Applied Science, Department of Field Crops, Kayseri, Türkiye

Abstract

Medicinal plants have been integral to traditional medicine for millennia, serving as vital resources for treating a wide range of ailments. This review explores the importance of these plants, focusing on their antioxidant properties and the phytochemicals responsible for their therapeutic effects. Approximately 10% of vascular plants are recognized for their medicinal qualities, with natural antioxidants, particularly phenolic compounds and flavonoids, playing a crucial role in health maintenance by scavenging free radicals. The review delves into the molecular mechanisms underlying antioxidant activities, including both enzymatic and non-enzymatic defenses, emphasizing their significance in combating oxidative stress. Notably, members of the Lamiaceae family exhibit diverse species with potent antioxidant capabilities. Various in vitro models are evaluated to assess these antioxidant properties, highlighting the potential of medicinal plants as sustainable sources of natural antioxidants. The findings underscore the relevance of these plants in modern pharmacology and nutrition, advocating for further research to standardize extraction methods and identify specific active compounds. Ultimately, the continued exploration of medicinal plants can contribute significantly to public health and the development of innovative therapies rooted in nature, enhancing our understanding of their role in promoting health and preventing disease.

Keywords: Medicinal plants, Bioactive Compounds, Oxidative Stress, Antioxidants, Free Radicals.

INTRODUCTION

Medicinal plants, also called medicinal herbs, have been discovered and used in traditional medicine since prehistoric times [1]. Plants synthesize hundreds of chemical compounds for various functions, including defense and protection against insects, fungi, diseases, and herbivorous mammals [2]. Ten percent of all vascular plants are used as medicinal plants, estimated to be between 350,000 and almost half a million species. Since ancient times, plants have been used in medicine and are still used today [3]. Herbal medicines or supplements are natural compounds from plants' leaves, bark, roots, seeds, or flowers that people can use for medicinal purposes [4]. The first written record of herbal medicine use showed up in 2800 B.C. in China. Since then, herbs have gained and fallen out of favor many times in the medical field. Medicinal plants refer to various plants with medicinal properties [5]. From the beginning of human existence, man has familiarized himself with plants and used them in various ways throughout the ages. People have been using plants as a traditional medicine for thousands of years [6]. Each medicinal plant that has been used in the conventional system of medicine must be scientifically tested to bring forth its active principle that might be effectively used as a phytomedicine. The parts of medicinal plants that may be used are different types of seeds, roots, leaves, fruit, skin, flowers, or even the whole plant [7]. Natural antioxidants are widely distributed in both food and medicinal plants. These natural antioxidants play a crucial role in maintaining health by exhibiting a wide range of biological effects [8]. Antioxidants play a pivotal role as scavengers of free radicals or active oxygen species. There are numerous reports of antioxidant activity in fruits, vegetables, and herbal compounds [9]. Herbal plants have long been used as safe, effective, and sustainable sources of natural antioxidants or free radical scavengers, particularly phenolic compounds, such as phenolic acids, flavonoids, tannins, stilbenes, and anthocyanins [10].

Vitamin C, vitamin E, selenium, βcarotine, lycopene, lutein, and other carotenoids have been used as supplementary antioxidants Plants' secondary metabolites such as flavonoids and terpenoids play an important role in the defense against free radicals [11]. Since ancient times, many plants have been used for medicinal purposes, helping to alleviate diseases [12]. Background Traditional medicine or ethnomedicine is a set of empirical practices embedded in the knowledge of a social group often transmitted orally from generation to generation with the intent to solve health problems [13]. It is estimated that 70–80% of people worldwide rely chiefly on traditional, largely herbal, medicine to meet their primary healthcare needs [14]. Antioxidants are inhibitors of redox reactions, even at very low concentrations [15]. Phenolic compounds and flavonoids are potential substitutes for bioactive agents in pharmaceutical and medicinal sections to promote human health and prevent and cure different diseases [16]. The main phytochemical components, present in medicinal plants are tannins, alkaloids, saponins, cardiac glycosides, steroids, terpenoids, flavonoids, phlorotannins, anthraquinones, and reducing sugars [17]. Numerous common pharmaceuticals, including anti-cancer, antiviral, and anti-diabetic drugs, are derived from traditional plant-derived medicines [18]. Phytochemicals are compounds found in plants that contribute to their color, flavor, and smell. These bioactive substances play a crucial role in the medicinal properties of herbs [19]. The importance of plants is known to us well. They are widely used in human therapy, veterinary, agriculture, scientific research, and countless other areas [20]. The most important of these bioactive constituents of plants are alkaloids, tannins, flavonoids, and phenolic compounds [21]. The Lamiaceae family is one of the largest families of flowering plants and includes various species with biological and medical uses [22]. Although several therapeutic molecules are being tested, no effective vaccines or specific treatments have been developed [23]. Many medicinal plants and their secondary metabolites are widely used to treat diseases such as malaria and dengue worldwide [24]. The traditional use of medicinal plants has played an important role in Turkey. The use of plants to cure diseases and relieve physical suffering has started from the earliest times of mankind's history [25]. Several proposed cellular actions or mechanisms explain medicinal plants' in vivo anti-inflammatory activity. These mechanisms include antioxidative and radical scavenging activities, and regulation of cellular activities of the inflammation-related cells [26].

Molecular Basis of Antioxidant Activity in Medicinal Plants

It is necessary to Screen out medicinal plants for their antioxidant potential. Therefore an attempt has been made to review different in vitro models for estimating the antioxidant properties of natural products from medicinal plants [27]. Antioxidant and radical scavenging activities are much higher in carrot peel than phloem and xylem tissue. Phenolic acids and flavonoids made a greater contribution to the total antioxidant capacity [28]. Several studies indicated that some Chinese medicinal plants possess more potent antioxidant activity than common fruits and vegetables, and phenolic compounds were a major contributor to the antioxidant activity of these plants [29]. However, chemical analysis showed that plants are a valuable source of a wide range of secondary metabolites, which are used as pharmaceuticals, agrochemicals, flavors, fragrances, colors, biopesticides, and food additives [30]. Thus, antioxidants are believed to be essential for the body's defense system against oxidative stress and the interest has increased remarkably in finding natural antioxidants for use both as new drugs and in foods and medicinal materials [31]. Phenolic acids constitute a group of potentially immunostimulating compounds. They occur in all medicinal plants and are widely used in phytotherapy and foods of plant origin [32]. Phenolic derivatives are one of the most important compounds that are found in secondary metabolites in plants [33]. They can be utilized in various fields such as antioxidant, antimicrobial, anti-inflammatory, antitumor, antiviral, analgesic, and antipyretic [34]. There are several endogenous antioxidant defensive mechanisms other than dietary against radical cell damage called enzymatic antioxidants. These include superoxide dismutase (SOD), catalase (CAT), glutathione reductase (GR), and glutathione peroxidase (GSH-Px). They have important roles in the metabolism of oxidative toxic metabolites. The enzymatic antioxidants assayed were superoxide dismutase, peroxidase, polyphenol oxidase, and catalase. Several enzymatic and non-enzymatic antioxidant defense mechanisms can eliminate reactive species [35]. It is well known that reactive oxygen species (ROS), such as superoxide anion (O2), hydroxyl radicals (OH), singlet oxygen (1O2), and hydrogen peroxide (H2O2), play a major role in the development of oxidative stress that can lead to many illnesses including cardiovascular diseases, diabetes, inflammation, degenerative diseases, cancer, anemia, and ischemia [36]. Plants may contain a wide variety of free radical scavenging molecules, such as phenolic compounds (e.g. phenolic acids, flavonoids, lignans, stilbenes, quinones, coumarins, tannins), nitrogen compounds (alkaloids, amines, betalains), vitamins, terpenoids (including carotenoids), and some other endogenous metabolites, which are rich in antioxidant activity [37].

Table 1: Antioxidant capacity and total phenolic content selected of some medicinal plants

Scientific Name	Family Name	Local Name	Utilizing Parts	Traditional Uses	References
*Melissa officinalis L.**	*Lamiaceae*	Lemon balm	Leaves	Cardiovascular diseases, asthma, carminative, digestive, and hiccup	[26]
*Lavandula angustifolia Miller subsp. Angustifolia **	*Lamiaceae*	Lavender	Flowers	Aromatic, carminative, antispasmodic, cosmetic, medicinal, antibacterial, and antiseptic	[30]
A. *ceterach**	*Aspleniaceae*	Golden herb	Whole	Infusion, kidney stones, and dirhem	[26]
*E. spectabilis**	*Xanthorrhoeaceae*	Foxtail lily	Roots Leaves	Fresh shoots and leaves, as food,	[29]
*C. pestalozzae**	*Asteraceae*	Chamomile	Whole	Infusions, reducing fever and Cholesterol, sudorific, and sedative	[22]
*Salvia hydrangea DC. Ex Benth**	*Labiatae*	Salvia officinalis	Herb	Clean wounds and treat sore throats, coughs, and dental abscesses.	[38]
*Coriandrum sativum L. **	*Umbelliferae*	Coriander	Seed	Stomachic, carminative, and digestive.	[39]
*Coriandrum sativum L. **	*Umbelliferae*	Cumin	Seed	Stomachic, carminative, and digestive.	[29]
*Trigonella foenum-graecum L**	*Fabaceae*	Fenugreek	Whole	Digestive issues, inflammation, and diabetes.	[22]
Nigella sativa L*	*Ranunculaceae*	Nigella (black seeds)	Seeds	Arthritis, asthma, inflammation, liver, and gastro disorders besides their potential role in diabetes and cancers	[40]
*Alo ebarbadensis L**	*Sphodelaceae*	*Aloe vera*	Leaves, Flowers, Roots	Conjunctivitis, Stomachic, Hemorrhoids and Diabetes. Skin burns, scalds, scrapes, Sunburn, wounds psoriasis, and others	[41]
*Cassia alata L**	*Moringaceae*	*Moringa oleifera*	Immmature seed pod, Leaves, Mature seeds, Oil pressed from seeds, Flowers and, Roots	Curing wounds, pain, ulcers, liver disease, heart disease, cancer, and inflammation.	[42]

Many fruits, vegetables, aromatic, spicy, medicinal, and other plants may contain bioactive compounds exhibiting free radical scavenging activity. Many medicinal plants include large amounts of antioxidants such as phenolic compounds, nitrogen compounds, vitamins, terpenoids, and other endogenous metabolites [43]. Several studies have been conducted with Lavender (*Lavandula angustifolia*) and carob (*Ceratonia siliqua L*.). These studies showed that these plants possess antipsoriatic, antitoxoplasmotic, antidiabetic, and antidiarrheal Properties [44]. Since antioxidants from medicinal plants are now considered promising therapeutic candidates for preventing the damage caused by free radicals, research on these compounds has grown significantly over time [45]. Depending on the mechanism of the relevant chemical reactions, antioxidant capacity analyses are divided into 3 classes: (i) single electron transfer (SET), (ii) hydrogen atom transfer (HAT) reaction-based assays, or (iii) chelation of transition metals. While SET-based assays measure the reducing capacity of the antioxidant, HAT-based assays measure its capacity to donate hydrogen atoms. The purpose of HAT and SET-based assays is to measure the radical scavenging capacity of a sample rather than its preventive antioxidant capacity [46]. The antioxidant activities of plant extracts depend on the extraction efficiency of the bioactive components and the composition of the extracts [47]. Essential oils of

SFU and SFT were obtained by hydrodistillation method using Clevenger apparatus, while 300 ml of distilled water was added to 20 g of each sample. The distillation procedure occurred in 3 h and the essential oil yields were calculated. Essential oil component analysis was made using GC-MS (gas chromatography [48].

Table 2: The tested extracts, total bioactive compounds, and total antioxidant capacity (by phosphoenol assays) [49]

Extracts	TPC (mgGAE/g)	TFC (mgRE/g)	PBD (mmolTE/g)
n-hexane	13.73 ±0.41[e]	9.04 ±0.44c	1.45 ±0.03[b]
Ethylacetate	18.25± 0.22[d]	19.73± 0.59[b]	1.85± 0.06[a]
DCM	19.66 ±0.53[c]	3.82± 0.65[e]	1.52 ±0.02[b]
Water	25.97 ±0.48a[b]	52.95± 0.34[a]	1.59 ±0.14[b]
Methanol	25.17 ±0.17[b]	2.66 ±0.04[e]	0.90 ±0.03[c]
Infusion	26.62 ±0.11[a]	7.33 ±0.04[d]	1.06 ±0.01[c]

Values are reported as mean SD. MeOH: Methanol; TPC: Total phenolic content; TFC: Total flavonoid content; PBD: Phosphomolybdenum; GAE: Gallic acid equivalent; RE: Rutin equivalent; TE: Troloxequivalent.Different superscripts indicate significant differences in the tested extracts *($p<0.05$).*

Superoxide dismutase (EC 1.15.1.1; SOD) catalyzes the dismutation of superoxide radicals to hydrogen peroxide and oxygen. In higher plants, SOD plays a major role in combating oxygen radical-mediated toxicity [50]. Oxidative stress is induced by a wide range of abiotic stresses. In addition, SOD proteins can bind to cell surface proteoglycans and extracellular matrix components in a positively-charged C-terminal region (extracellular matrix binding region). The efficacy of SODs makes sthemmorewidely used in medical, food, and skincare products [51]. Superoxide dismutase (SOD) is the first detoxification enzyme and the most powerful antioxidant in the cell. It is an important endogenous antioxidant enzyme that acts as a component of a first-line defense system against reactive oxygen species (ROS) [52]. SODs are classified into three types based on their metal cofactor: (i) Fe-SOD (localized to chloroplasts); (ii) Mn-SOD (localized to mitochondria) and (iii) Cu/Zn-SOD (localized to chloroplasts, peroxisomes, and cytosol) [53]. In plants, catalase scavenges H2O2 generated during mitochondrial electron transport, oxidation of fatty acids, and most importantly photos respiratory oxidation [54]. Before we consider how other radicals are derived from oxygen radicals, it is necessary to mention some normal physiological processes that lead to the formation of oxygen radicals [52]. Hydrogen peroxide (H2O2) is produced predominantly in plant cells during photosynthesis and photorespiration, and to a lesser extent, in respiration processes. It is the most stable of the so-called reactive oxygen species (ROS) and therefore plays a crucial role as a signaling molecule in various physiological processes [55]. Glutathione peroxidases are a family of multiple S02fu isozymes that catalyze the reduction of H2O2, and organic hydroperoxides by alleviating and thus help to protect the cells against oxidative damage [56]. Extracts from the parenchymous leaf-gel of the Aloe vera plant (Aloe barbadensis Miller) were shown to contain glutathione peroxidase (GSHPx) activity [57]. These enzyme inhibitors may be used to improve chemotherapy or treat various diseases. In recent years, the concern about chemotherapy has been raised mostly about anticancer drug resistance [58]. When any of these exceed the optimum tolerance, this results in stress on the plant, affecting its developmental, structural, physiological, and biochemical processes [59]. All aerobic organisms, including plants, produce ROS naturally. The biotic and abiotic stresses cause what is called oxidative damage in plants as a result of free radicals, or ROS [60]. Medicinal plants may also produce non-enzymatic molecules including ascorbate, glutathione, carotenoids, and anthocyanins which eliminate, counteract, and scavenge the ROS in plant systems and protect the main enzymes from ROS [61]. The antioxidant activity of a bioactive compound refers to its ability to preserve cellular function and structure by removing free radicals that cause lipid peroxidation and other oxidative harm [62]. Phenolic compounds have been shown to positively affect human health, lowering the risk of diabetes, cancer, cardiovascular disease, and neurological problems [63]. However, the obtainment of crude extracts with a stable quantity of bioactive compounds is still difficult due to the influence of various abiotic and biotic environmental factors on the phytochemical composition of field-grown plants [64]. Ascorbic acid (Vitamin C) is widely recognized as a mainly naturally occurring antioxidant in biological systems. It has been reported that vitamin C can synergistically regenerate vitamin E, resulting in an enhancement of antioxidant activity in membranes [65]. The use of plant cell and tissue culture methodology as a means of producing medicinal metabolites has a long history. Cultured plant cells synthesize, accumulate, and sometimes exude many classes of metabolites. Medicinal compounds are of particular interest and much effort has been devoted to obtaining some of the most active and precious therapeutics.[66] Vitamin C is an electron donor and therefore a reducing agent. All known physiological and biochemical actions of vitamin C are due to its action as an electron donor. Ascorbic acid donates two electrons from a double bond between the second and third carbons of the 6-carbon molecule [67]. Antioxidants in medicinal plants are chemically variable secondary metabolites that are synthesized in various parts of the plant at different vegetation stages [68].

Table 3: HPLC-PDA quantification of rosmarinic acid in NADES and 70 % ethanol extracts of plants from the Lamiaceae family for rosmarinic acid (mg/g dry weight of plant material) [69]

Sample/ Solvent	**ChCl: CitA (1:1)**	**ChCl: Ur (1:1)**	**ChCl: Fru (1:1)**	**ChCl:1,2PD (1:1)**	**70 % EtOH**
Melissa officinalis	12.85 ± 0.65^{b}	15.69 ±0.73$^{'a}$	10.27 ± 0.73^{c}	13.28 ±0.76^{b}	17.49 ± 0.55^{a}
Thymus serpyllum	4.08 ± 0.05^{a}	3.86 ± 0.24^{a}	3.80 ± 0.32^{a}	4.69 ±0.69$^{'a}$	4.26 ± 0.31^{a}
Lavandula angustifolia	3.12 ± 0.49^{a}	4.50 ± 0.07^{a}	3.68 ± 0.45^{a}	4.11 ±0.49^{a}	4.01 ± 0.25^{a}
Salvia Rosmarinus	13.00 ± 0.98$^{'a}$	6.50 ± 0.37^{b}	7.56 ± 0.41^{b}	12.36 ±1.29^{a}	8.24 ± 0.48^{b}
Satureja hortensis	11.52 ± 1.04^{a}	9.75 ± 0.22a, ^{b}	8.64 ± 0.14^{b}	10.89 ±0.32^{a}	10.68 ± 0.74'a, ^{b}
Ocimum basilicum	5.35 ± 0.82$^{'a, b}$	5.60 ± 0.60$^{'a, b}$	4.05 ± 0.63^{b}	6.57 ±0.56^{a}	5.73 ± 0.16a, ^{b}
Origanum vulgare var.	4.08 ± 0.05^{a}	3.86 ± 0.24^{a}	3.80 ± 0.32^{a}	4.69 ±0.69'a	4.26 ± 0.31^{a}

*The results are expressed as the mean of two independent measurements ±stan dard deviation. Using Tukey's test, Different letters in a row indicate significant differences at p <0.05. Abbreviations: ChCl: choline chloride; CitA: citric acid; Ur: urea; Fru: fructose; 1,2-PD: 1,2-propanediol. All NADES were prepared at a 1:1 molar ratio.

Vitamin E, including tocopherols and tocotrienols, comprises lipid-soluble antioxidants that modulate lipid peroxidation [70]. The vitamin E, i.e. chroman-6-ols collectively tocochromanols (tocopherols + tocotrienols), is generally ingested with fat-containing foods. Good sources are vegetable oils, nuts and nut oil seeds, egg yolk, margarine, cheese, soya beans, wheat germ, oatmeal, avocados, olives, and green leaf vegetables [71]. Carotenoids are naturally existing pigment compounds that give the orange, deep yellow, and red colors to fruits and vegetables such as tomatoes, carrots, and sweet potatoes [72]. There are several dozen carotenoids in the foods we eat, and most of these carotenoids have antioxidant activity that has been best studied since, in most countries, it is the most common carotenoid in fruits and vegetables. The biosynthetic sequence of the carotenoids in plants is as follows: (1) phytoene (2) phytofluene (3) carotene (4) neurosporene (5) lycopene (6) carotene and (7) carotene [73]. Currently, carotenoids are used commercially as feed additives, animal feed supplements, natural food colorants, nutrient supplements, and, more recently, as nutraceuticals for cosmetic and pharmaceutical purposes [74]. Mechanisms of the antioxidant action exerted by carotenoid pigments in different processes. The electron transfer from the characteristic conjugated polyene chain of carotenoids to chlorophylls (A). Physical quenching of single oxygen (B). Electron transfer, hydrogen abstraction, and radical addition in the antioxidant activity against peroxyl radicals [75]. Polyphenols are the most significant compounds for the antioxidant properties of plant raw materials. The antioxidant activity of polyphenols is mainly due to their redox properties, which allow them to act as reducing agents, hydrogen donors, singlet oxygen quenchers, metal chelators, and reductants of ferryl hemoglobin [76]. Flavonoids and phenolic acids are widely distributed in higher plants and form part of the human diet. Recent interest in these substances has been stimulated by the potential health benefits arising from the antioxidant activity of these polyphenolic compounds [77].

Phytochemical Diversity in Medicinal Plants

Phytochemicals (from the Greek word phyto, meaning plant) are biologically active, naturally occurring chemical compounds found in plants, which provide health benefits for humans further than those attributed to macronutrients and micronutrients. Plant products have been part of phytomedicines since time immemorial. This can be derived from bark, leaves, flowers, roots, fruits, and seeds [78]. The common extraction techniques include soxhlet extraction, hydrodistillation, solvent extraction, supercritical fluid extraction (SFE), microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE), pulsed electrical field extraction (PEF), enzyme-assisted extraction (EAE), accelerated solvent extraction (ASE) and high hydrostatic pressure extraction (HHP) [79]. The pharmacological benefits of medicinally important plants are primarily due to bioactive phyto chemicals produced in the plant tissues as primary and secondary metabolites. These constituents have been identified as alkaloids, glycosides, flavonoids, phenolics, saponins, tannins, essential oils, and steroids [80]. The correlation between the phytoconstituents and the bioactivity of plants is desirable to know for the synthesis of compounds with specific activities to treat various health ailments and chronic diseases as well [81]. Flavonoids are an essential group of naturally occurring polyphenolic compounds, and their flavan nucleus characterizes them. It is among the most common compounds in vegetables, fruits, and plant-derived beverages. Flavonoids are considered health-promoting and disease-preventing dietary supplements [82]. Moreover, the biological activity of such medicinal plants against certain human pathogenic bacteria and fungi is poorly investigated, and a literature search indicated limited information about the antimicrobial activity [83]. Investigated the biological activities and therapeutic properties of flavonoids, such as antioxidant, anti-inflammatory, antiviral, and anti-cancer effects [84]. Use analytical techniques like HPLC (High-Performance Liquid Chromatography) or LC-MS (Liquid Chromatography-Mass Spectrometry) to identify and quantify specific flavonoids present in medicinal plants [85]. Medicinal herbs rich in flavonoid compounds encompass several botanical plant species, e.g. Viola tricolors L., Solidago virgaurea L., Hypericum perforatum L., Betula sp. Ehrh., Crataegus oxyacantha L., and many others [86]. Multiple combinations of phytochemicals can result in a synergistic activity that increases their beneficial effects at molecular, cellular, metabolic, and temporal levels, offering advantages over chemically synthesized drug-based treatments [87]. Epigenetic modifications refer to the transmissible changes in gene expression and chromatin structure that occur without a physical change in the DNA sequence. These changes are heritable and reversible and are crucial for the maintenance of cellular identity and the regulation of vital cellular processes [88]. Flavonoids and phenolic acids make up one of the most pervasive groups of plant phenolics. Plants and herbs consumed by humans may contain thousands of different phenolic acid and flavonoid components [89]. Medicinal plants have long been reported as a prospective hub of natural antioxidant compounds, particularly plant secondary metabolites i.e., phenolic compounds and flavonoids which are generated by plants to defend themselves or to promote growth under unfavorable conditions. In addition, functional group arrangement, configuration, substitution, and the number of hydroxyl groups were also influenced by the antioxidant activity of flavonoids, for example, radical scavenging activity and/or metal ion chelation ability [90]. Currently, polyphenols have attracted great attention and are of high importance due to their antioxidant activity. The pharmacological activities of many plants, fruits, and vegetables are closely related to the presence of natural antioxidants especially, phenolic acids and flavonoids [91]. Caffeic acid and ferulic acid can modulate the expression of genes involved in antioxidant defense pathways, such as Nrf2 (Nuclear factor erythroid 2-related factor 2) and its target genes (e.g., HO-1, NQO1) [92]. Caffeic acid and ferulic acid exhibit direct antioxidant properties by scavenging free radicals and reactive oxygen species, which can reduce oxidative stress-induced damage to cells and tissues [93]. Terpenoids, also known as isoprenoids, are a diverse class of natural compounds found in medicinal plants that play essential roles in various biological activities [94]. Terpenoids like α-bisabolol, curcumin, and artemisinin exhibit anti-inflammatory effects by modulating inflammatory pathways and cytokine production, making them valuable in the treatment of inflammatory disorders [95]. Terpenoids from medicinal plants are used in traditional medicine and modern drug development for their therapeutic potential. Carotenoids and limonene are bioactive compounds found in various fruits, vegetables, and plants, each playing crucial roles in cell communication and metabolic processes [96]. Limonene is a monoterpene compound found in citrus fruits and various plants. It has been studied for its role in cellular communication, particularly in modulating signaling pathways associated with inflammation, cell proliferation, and apoptosis [97]. In medicinal plants, morphine, and quinine can also be found naturally and have been used for their analgesic and anti-malarial properties for centuries [98]. Morphine is derived from the opium poppy plant and is a potent analgesic due to its ability to bind to opioid receptors in the central nervous system. This natural compound has been used for pain relief in traditional medicine practices [99]. Quinine, on the other hand, is extracted from the bark of the cinchona tree and has been used as an anti-malarial treatment. Its mechanism of action involves interfering with the parasite's ability to break down hemoglobin, ultimately leading to the death of the parasite. In medicinal plants, these natural compounds provide a source of analgesic and anti-malarial properties that have been utilized for their therapeutic benefits [100]. Glucosinolates and allyl sulfides are bioactive compounds found in medicinal plants that have been studied for their detoxification processes and potential anti-carcinogenic effects [101]. Allyl sulfides, on the other hand, are compounds found in garlic, onions, and other allium vegetables. These compounds have been studied for their potential anti-carcinogenic effects, with research suggesting that they may help inhibit the growth of cancer cells and reduce the risk of certain types of cancer [102].

Mechanistic Insights and Health Benefits

Antioxidants and phytochemicals play a crucial role in the neutralization of free radicals and the regulation of reactive oxygen species (ROS). At the molecular level, antioxidants such as flavonoids, carotenoids, and polyphenols donate electrons to free radicals, thereby stabilizing them and preventing oxidative stress. Prolonged oxidative stress and inflammation in the microenvironments of the prostate, attributable to factors like aging, exposure to carcinogens, dietary patterns, obesity, and genetic anomalies, can potentially stimulate heightened cellular proliferation leading to benign prostate hyperplasia (BPH), or prompt oncogenic reprogramming of prostate epithelial cells, culminating in prostate carcinogenesis [103].

Free Radical Scavenging and ROS Regulation

Recent advancements in the understanding of free radicals and reactive oxygen species (ROS) within biological systems are catalyzing a transformative shift in medical science, heralding a promising era for the management of health and disease [104]. The principal oxygen-containing free radicals implicated in numerous disease conditions include the hydroxyl radical, superoxide anion radical, hydrogen peroxide, singlet oxygen, hypochlorite, nitric oxide radical, and peroxynitrite radical. These highly reactive species can damage biologically significant molecules such as DNA, proteins, carbohydrates, and lipids within cellular nuclei and membranes. Their actions result in cell damage and disturbance of physiological balance [105].

Free radicals and other reactive oxygen species (ROS) originate from normal metabolic processes within the human body and external factors such as X-ray exposure, ozone, cigarette smoke, air pollutants, and industrial chemicals [106]. Their production is ongoing within cells due to enzymatic and non-enzymatic reactions. Enzymatic processes that contribute to free radical generation include those in the respiratory chain, during phagocytosis, in prostaglandin synthesis, and within the cytochrome P-450 system [107].

Free radicals such as superoxide anion (O_2-), hydrogen peroxide (H_2O_2), hydroxyl radical (OH), organic hydroperoxides (ROOH), alkoxy (RO), peroxy (ROO) radicals, hypochlorous acid (HOCl), and peroxynitrite (ONOO-) play crucial roles in cellular physiology and pathology. These reactive species are involved in oxidative stress pathways, damaging biomolecules like DNA, proteins, and lipids, which can disrupt cellular function and contribute to disease progression. Understanding their mechanisms and interactions is essential for elucidating their dual nature as both essential signaling molecules and agents of oxidative damage in biological systems [105-109].

Modulation of Redox-sensitive Signaling Pathways

Recently, there has been significant attention given to the antioxidant capabilities of natural substances. Specifically, these substances are believed to prevent the generation of free radicals, neutralize them through non-enzymatic methods, or boost the effectiveness of natural antioxidants within the body.[110] Polyunsaturated fatty acids (PUFAs) found in cholesterol esters, phospholipids, and triglycerides are susceptible to oxidation initiated by free radicals and can subsequently engage in chain reactions. A significant characteristic of lipid peroxidation is the degradation of polyunsaturated fatty acids (PUFAs), which produce a diverse range of electrophilic "short-chain aldehydes" with carbon chains ranging from 3 to 9 atoms, further enhancing biomolecular damage. Based on their structural properties, these reactive short-chain aldehydes formed from lipid peroxidation can be broadly categorized into 2-alkenals, 4-hydroxy-2-alkenals, and keto-aldehydes [111, 112].

CONCLUSİON

Medicinal plants continue to be invaluable in both traditional and modern medicine, particularly due to their rich array of bioactive compounds with antioxidant properties. The evidence presented indicates that these plants not only alleviate health issues but also protect against oxidative stress, a significant contributor to numerous chronic diseases. Future research should focus on the standardization of extraction methods and the identification of specific active compounds to enhance the therapeutic application of these plants. Additionally, understanding the mechanisms by which these phytochemicals exert their effects will pave the way for the development of innovative, plant-derived therapies. As interest in natural products grows, harnessing the potential of medicinal plants can contribute significantly to public health and the advancement of sustainable medicinal practices.

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