Review Article Open Access

Functional food applications of *Rosmarinus officinalis*: Antioxidant, anti-inflammatory, and metabolic health perspectives

Gohar Arajyan[1,2,3*], Sona Sargsyan[4], Varduhi Hovsepyan[1,2], Nvard Pahutyan[1], Qristine Navoyan[1], Milena Shahinyan[1], Gayane Melyan[5], Ivan Gabrielyan[6]

[1]Scientific Technological Center of Organic and Pharmaceutical Chemistry NAS RA, 26 Azatutyan Ave, 0014, Yerevan, Armenia; [2]Armenian State Pedagogical University after KH. Abovyan, 17 Tigran Mets str., Yerevan, Armenia; [3]University of Traditional Medicine, 38a Marshal Babajanyan Str., Yerevan, Armenia; [4]Yerevan State University, 1 Alek Manukyan St., 0025, Yerevan, Armenia; [5]Scientific Center of Agrobiotechnology" branch of the Armenian National Agrarian University, Isi Le Mulino 1, Etchmoadzin 1101, Armenia; [6]Department of Palaeobotany, A.Takhtajan Institute of Botany of the NAS RA, Acharyan 1, 0040, Yerevan, Armenia;

***Corresponding author:** Gohar Arajyan, PhD., Associate professor, Pharmacology and Pathohistology laboratory; Scientific Technological Center of Organic and Pharmaceutical Chemistry NAS RA, 26 Azatutyan Ave, 0014, Yerevan, Armenia

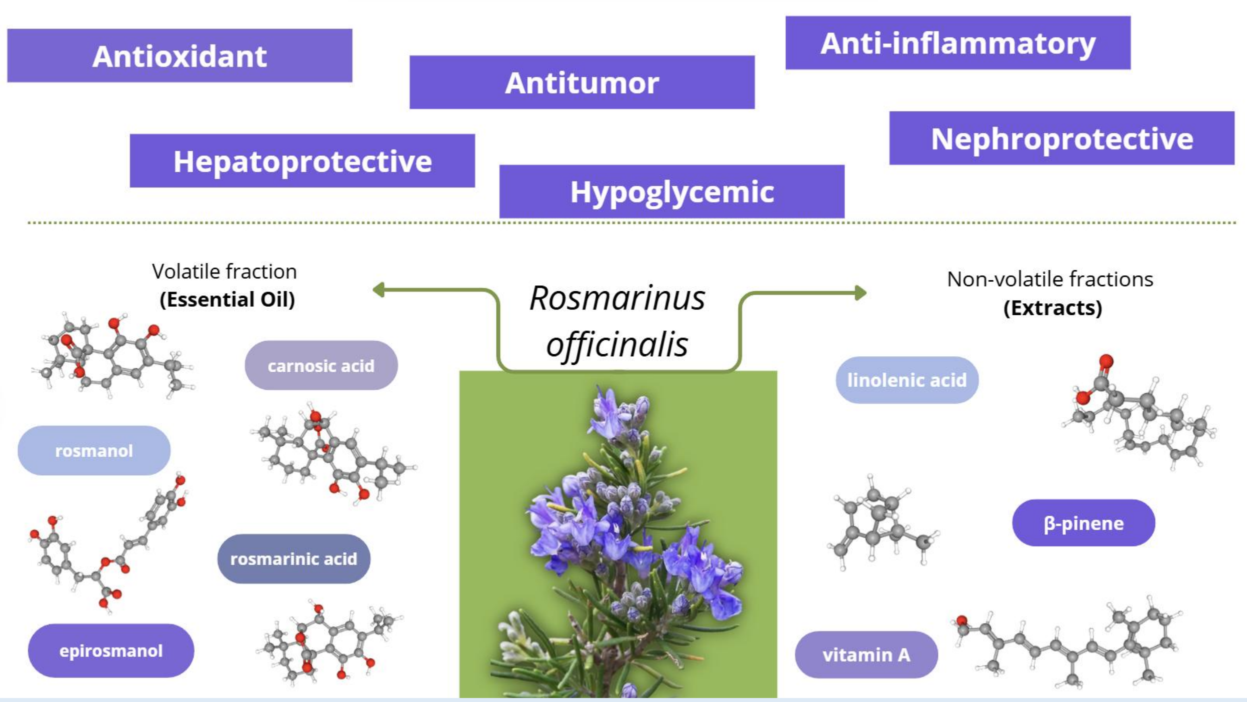
Submission Date: August 27th, 2025, **Acceptance Date:** October 2nd, 2025, **Publication Date:** October 11th, 2025

Please cite this article as: Arajyan G., Sargsyan S., Hovsepyan V., Pahutyan N., Navoyan Q., Shahinyan M., Melyan G., Gabrielyan I. Functional food applications of *Rosmarinus officinalis:* Antioxidant, anti-inflammatory, and metabolic health perspectives. *Functional Food Science* 2025; 5(10): 496 - 512. DOI: https://doi.org/10.31989/ffs.v5i10.1756

ABSTRACT

Rosmarinus officinalis L. (rosemary), a well-known aromatic herb of the Lamiaceae family, has long been valued for its culinary, medicinal, and industrial applications. Unlike previous reviews, this study integrates updated evidence (1998–2025) on rosemary's phytochemical composition, highlighting how geographical origin, environmental conditions, and extraction methods influence its bioactive profile. Rich in rosmarinic acid, carnosic acid, carnosol, and essential oils, rosemary exhibits diverse biological activities, including antioxidant, anti-inflammatory, antitumor, neuroprotective, cardioprotective, hepatoprotective, and antidiabetic effects. The graphical abstract 1 illustrates the major bioactive constituents of *Rosmarinus officinalis* L. and highlights their therapeutic potentials, emphasizing its role as a promising functional food and medicinal plant.This review uniquely emphasizes rosemary's functional food potential, including applications in food preservation, active packaging, and health-promoting dietary interventions. Mechanistic insights reveal that rosemary bioactives act through enhancement of antioxidant defenses, modulation of inflammatory pathways, regulation of apoptosis, and restoration of metabolic balance. By synthesizing mechanistic, pharmacological, and functional food perspectives, this review provides a novel, comprehensive resource for future research and practical applications in nutrition and therapeutics.

Keywords: *rosemary, rosmarinic acid, carnosic acid, carnosol, antioxidant, functional food*



Graphical abstract: Bioactive constituents and therapeutic potentials of *Rosmarinus officinalis* L.

INTRODUCTION

Rosmarinus officinalis L. is a perennial aromatic shrub belonging to the Lamiaceae family, traditionally valued both as a culinary spice and a medicinal plant [1]. Native to the Mediterranean basin and now cultivated worldwide, rosemary has been used for centuries in folk medicine as a memory enhancer, digestive aid, and natural remedy for inflammatory conditions [2]. Advances in phytochemistry and pharmacology have confirmed its richness in bioactive compounds, including phenolic acids (rosmarinic acid), diterpenes (carnosic acid, carnosol), flavonoids, and essential oils, which collectively account for its broad spectrum of biological activities [3].

In this review we adopt the Functional Food Center (FFC) and Functional Food Institute (FFI) definitions, in which functional food is defined as a natural or processed food that contains known biologically active compounds, in defined amounts, and which is shown to provide clinically proven health benefits beyond basic nutrition. Bioactive compounds are defined as constituents in foods or dietary supplements that are responsible for these health benefits.

Modern biomedical and nutritional research increasingly emphasizes the role of oxidative stress, chronic inflammation, and metabolic dysregulation in the development of non-communicable diseases such as cardiovascular disorders, type 2 diabetes, neurodegeneration, and cancer. Natural products rich in antioxidants and anti-inflammatory agents, such as rosemary, are therefore attracting significant attention as complementary therapeutic and preventive strategies [4]. In addition to its pharmacological effects, rosemary has gained prominence as a natural preservative in the food industry due to its ability to delay lipid oxidation, inhibit microbial growth, and extend shelf life, while simultaneously offering health-promoting benefits [5,6]. Rosemary also represents a promising candidate for functional food applications, bridging the gap between nutrition and medicine [7, 8, 9].

The concept of functional foods has gained increasing global attention, with scientists, public health experts, and food producers highlighting their potential to reduce pharmaceutical side effects and healthcare costs while supporting the management of chronic diseases. Comprehensive resources in this field provide a foundation for understanding functional food science, its components, and its societal relevance [10].

This review synthesizes recent findings on rosemary's phytochemical composition, biological mechanisms, and therapeutic potential, with particular focus on antioxidant, anti-inflammatory, and metabolic health perspectives. By integrating insights from pharmacology, nutrition, and food science, we highlight rosemary's potential as a multifunctional natural agent in chronic disease prevention and functional food development.

RESEARCH METHOD

A comprehensive literature search was conducted across the databases PubMed, ScienceDirect, FFHDJ.com, and Web of Science to collect up-to-date information on the pharmacological activities and major phytochemical constituents of *Rosmarinus officinalis*. Publications from 1998 to 2025 were considered. The search employed the following keywords: "rosemary," "*Rosmarinus officinalis*," "rosmarinic acid," "carnosol," and "carnosic acid." Inclusion criteria encompassed peer-reviewed original research articles, reviews, and experimental studies relevant to the pharmacological and phytochemical properties of rosemary. Studies lacking adequate methodological detail, non-peer-reviewed sources, or unrelated topics were excluded. This approach ensured a broad, current, and reliable overview of the subject.

Family - **Lamiaceae Martinov**
Species - ***Rosmarinus officinalis*** **L.**

Rosmarinus officinalis belongs to the sage family, Lamiaceae, one of the largest families of flowering plants, comprising approximately 236 genera and 6,900–7,200 species worldwide [11, 12].

Members of this family are well known for their aromatic essential oils and include many culinary and medicinal herbs such as basil, lavender, mint, sage, and thyme [11, 13]. They are rich in bioactive compounds, including terpenes, iridoids, flavonoids, and phenolic acids—especially rosmarinic acid, which exhibits antibacterial, antiviral, antioxidant, and anti-inflammatory properties [11].

Botanical Description and Extraction of Bioactive Compounds from *Rosmarinus officinalis*: Rosemary, originally classified by Carl Linnaeus, is native to the temperate Mediterranean region. According to the new classification, it is included also in the genus *Salvia* as *Salvia rosmarinus* Spenn. Rosemary is a evergreen shrub with blue-white, pink, or purple flowers and typically grows up to 1 meter tall [14, 15]. The leaves are sessile, linear to lanceolate (1–4 cm long, 2–5 mm wide), dark green on top, and white, tomentose underneath, with a strong characteristic aroma [16, 15, 17]. Numerous cultivars exist, and the plant is cultivated in many countries from China to South America.

Chemical Composition of Rosemary: The chemical composition of rosemary is characterized by a complex mixture of monoterpenes, terpenoids, and phenolic acids, which collectively contribute to its aromatic and bioactive properties. Steam-distilled rosmary essential oils (REO) analyzed by GC–MS and GC–FID from Morocco, Italy, and France revealed a robust monoterpenoid profile, with 1,8-cineole (eucalyptol), α-pinene, β-pinene, camphor, caryophyllene, and D-limonene as the predominant constituents [18]. The petroleum ether fraction obtained after ethanol extraction (PEF-RO) contained 82 compounds, including hydrocarbons, ketones, alcohols, phenols, and esters, with major constituents such as verbenone, vitamin A, trans-geraniol, linolenic acid, and 1,8-eucalyptol [19]. Innovative extraction techniques, such as homogenate-ultrasonic pretreatment followed by microwave hydrodistillation (HUP-MHD), improve yield and help preserve characteristic monoterpenes such as α-pinene, 1,8-cineole, camphor, verbenone, and borneol [20]. Geographical and seasonal variations significantly influence the volatile profile. For example, GC–MS analysis of REO from Southwestern Romania identified 36–41 compounds accounting for 98–99% of the total oil, with oxygenated monoterpenes (56.82–66.94%) and monoterpene hydrocarbons (30.06–40.28%) as dominant. The major compounds included camphor, 1,8-cineole, and α-pinene, along with minor components including camphene, α-myrcene, β-pinene, α-terpinene, linalool, terpinolene, and carvacrol [21]. Overall, REO and extracts are rich in bioactive compounds such as α-pinene, camphor, 1,8-cineole, carnosic acid, and rosmarinic acid, which underlie its antioxidant, antimicrobial, and anti-inflammatory activities [22].

The essential oil of rosemary also contains flavonoids, terpenes, phenylpropanoic acids, quinones, and steroids, which contribute to its broad pharmacological activities, including antimicrobial, anti-inflammatory, antioxidant, antitumor, hypoglycemic, hypolipidemic, hepatoprotective, and nephroprotective effects. Among these, 17 compounds have been identified as potential quality markers (Q-markers) based on their measurability, medicinal relevance, and therapeutic effectiveness. These include carnosic acid, carnosol, rosmanol, isorosmanol, epirosmanol, 7-methoxyrosmanol, 7-ethoxyrosmanol, rosmaridiphenol, rosmadial, rosmarinic acid, 1,8-cineole, rosmarinine, royleanone, horminone, homovanillic acid, ferruginol, and cryptotanshinone [23]. The chemical composition of REO is strongly influenced by geographical origin, environmental conditions, and extraction methods. A comprehensive review by Rafya et al. (2024) highlighted this variability, showing that samples from Jerada, Morocco, were predominantly composed of 1,8-cineole (42.3%), α-pinene (11.6%), and camphor (10.5%). These findings emphasize the importance of considering regional and environmental factors when evaluating REO [24].

Environmental stress also affects phytochemical composition and bioactivity. For instance, Laftouhi et al. (2024) reported that different water stress levels (40%, 60%, and 80%) significantly altered the primary and secondary metabolites of REO, with α-pinene, camphor, 1,8-cineole, and rosmarinic acid as the major compounds. Notably, REO obtained under 60% water stress exhibited the highest antioxidant activity, whereas oil from the 80% stress condition demonstrated the strongest antidiabetic effects through α-amylase and α-galactosidase inhibition [25].

Similarly, REOs from two regions in eastern Morocco, Taourirt and Jerada, showed variations in composition: 1,8-cineole (53.6% in RoEOT and 42.3% in RoEOJ), α-pinene (12.3% and 11.6%), and camphor (9.6% and 10.5%). Both oils demonstrated significant antioxidant capacity in DPPH, FRAP, and β-carotene bleaching assays [26].

Comparable results were obtained in Tunisian wild REOs, dominated by oxygenated monoterpenes (1,8-cineole 42.3%, α-pinene 11.6%, and camphor 10.5%), which also showed strong antioxidant, antibacterial, and anti-biofilm activities [27]. Additionally, hydroalcoholic extracts from wild and cultivated rosemary, analyzed by LC-MS, revealed carnosic acid, carnosol, and rosmarinic acid as major bioactive compounds. Both types of extracts displayed high polyphenol and flavonoid content, strong antioxidant activity, and inhibitory effects on α-amylase, acetylcholinesterase, and butyrylcholinesterase enzymes. Wild REs (RE) contained higher bioactive content and stronger activity than cultivated ones [28].

These studies demonstrate that geographical origin, cultivation conditions, and environmental stress strongly influence the chemical composition and bioactivity of REOs and extracts, reinforcing their therapeutic potential.

The therapeutic potential of rosemary is illustrated in Table 1, which summarize its major pharmacological activities, associated phytochemicals, biological targets, and experimental models.

Table 1. Therapeutic activities and supporting evidence for Rosmarinus officinalis L.

Therapeutic Activity	Major Bioactive Compounds	Mechanisms of Action	Supporting Evidence/Models
Antioxidant	Carnosic acid, carnosol, rosmarinic acid, flavonoids, essential oils	Scavenging free radicals, enhancing antioxidant enzymes (CAT, SOD, GPx), Nrf2 activation, reducing lipid peroxidation	In vitro assays (DPPH, FRAP, ABTS); broiler models; food preservation studies
Anti-inflammatory	Carnosic acid, carnosol, rosmarinic acid, α-pinene, eucalyptol	Inhibition of NF-κB, MAPK, STAT3, NLRP3 inflammasomes; suppression of cytokines (TNF-α, IL-1β, IL-6) and prostaglandins	In vitro assays, animal models (fructose-induced inflammation); human clinical trial (intubation study)
Antitumor	Carnosic acid, rosmarinic acid, carnosol, ursolic acid	Induction of apoptosis, ROS generation, inhibition of AKT/mTOR and STAT3 pathways, antiangiogenic activity, epigenetic modulation	Cancer cell lines (breast, liver, colon), mouse xenografts, molecular docking studies
Neuroprotective	Rosmarinic acid, carnosic acid, flavonoids, essential oils	Antioxidant defense, inhibition of apoptosis, modulation of neurotransmission, neurogenesis, connexin 43 regulation	Models of ADHD, heavy metal toxicity, ischemic stroke, diabetic neuropathy; aromatherapy studies
Cardioprotective	Carnosic acid, carnosol, rosmarinic acid, flavonoids, ursolic acid	Vasorelaxation via KCNQ4/5 channels, COX-2 selective inhibition, regulation of calcium homeostasis, SIRT1/PI3K/AKT activation	Animal models of myocardial infarction and heart failure; in vitro vascular assays
Antidiabetic & Hepatoprotective	Carnosic acid, carnosol, rosmarinic acid, essential oils, terpenoids	Reduction of oxidative stress, improvement of glucose metabolism, inhibition of α-amylase/α-glucosidase, protection of liver/kidney function	Streptozotocin-induced diabetic rat models; hepatocellular carcinoma models
Food Preservation/Functional Food	Phenolic diterpenes, rosmarinic acid, essential oils	Delay of lipid oxidation, antimicrobial effects, improvement of sensory properties, encapsulation for stability	Meat, dairy, and oil preservation studies; active packaging applications

Antioxidant Effect of Rosemary: RE and REO are potent natural antioxidants that enhance the thermo-oxidative stability of vegetable oils. By delaying lipid oxidation, they help preserve physicochemical integrity during storage and frying, reduce harmful oxidation products, and extend shelf life while maintaining nutritional and sensory qualities. These properties underscore rosemary's potential as a sustainable alternative to synthetic preservatives in the food industry [29].

In broiler chickens, dietary supplementation with fresh rosemary leaf powder (0.5–2%) significantly enhanced antioxidant defenses. Rosemary increased the activities of catalase, total superoxide dismutase, and overall antioxidant capacity in both serum and liver, while decreasing malondialdehyde levels, a key marker of lipid peroxidation. At the molecular level, rosemary upregulated the expression of critical antioxidant genes, including nuclear factor E2-related factor 2, glutamate–cysteine ligase modifier subunit, and superoxide dismutase 1. These results demonstrate that rosemary bioactive compounds function as potent natural antioxidants, enhancing oxidative stability and promoting overall health in poultry [30].

Rosemary hydroalcoholic macerates also exhibit strong antioxidant properties due to their high content of polyphenols, particularly carnosic acid and rosmarinic acid. In one study, a 70% ethanol macerate of Dobrogean rosemary showed the highest total polyphenol content, measured at 2155 ± 2.45 milligrams of gallic acid equivalents per 100 grams of fresh weight, which correlated with substantial antioxidant activity of 745 ± 2.33 milligrams of gallic acid equivalents per 100 grams of fresh weight. These findings demonstrate that rosemary bioactive compounds effectively scavenge free radicals and protect against oxidative damage, supporting their potential use in antioxidant-rich dermatocosmetic formulations [31].

Rosemary is a rich source of natural antioxidants, mainly due to compounds such as carnosol and rosmarinic acid, which effectively counteract oxidative stress. These bioactive compounds scavenge free radicals, reduce lipid peroxidation, and protect cellular components from oxidative damage. The antioxidant properties of rosemary contribute to many of its pharmacological benefits, including neuroprotection, cardiovascular support, and the maintenance of overall cellular health, highlighting its potential as a natural agent for the prevention or management of disorders associated with oxidative stress [32, 33].

Moist heat-treated RE has been shown to exhibit greater antioxidant activity compared with untreated extracts. Key bioactive compounds, including rosmarinic acid, ellagic acid, gallic acid, and rutin, were present at higher concentrations in the heat-treated extract. Radical scavenging activity, assessed by the DPPH assay, revealed a lower half-maximal inhibitory concentration for the heat-treated extract compared with the untreated extract, while total antioxidant capacity and ferric reducing antioxidant power were also increased. These findings suggest that moist heat treatment enhances the release of rosemary bioactive compounds, substantially improving their antioxidant potential [34].

The effect of light-emitting diode light conditions on the antioxidant activity of rosemary has also been investigated. Plants grown under red light exhibited the highest radical scavenging activity, with DPPH and ABTS values of 87.72 ± 0.60% and 17.16 ± 0.65%, respectively. Exposure to red light also increased total phenolic content to 126.72 ± 1.47 milligrams of gallic acid equivalents per gram and total flavonoid content to 21.02 ± 1.61 milligrams of quercetin equivalents per gram, with rosmarinic acid identified as the predominant phenolic compound. These findings indicate that optimizing light conditions can enhance the antioxidant potential of rosemary, supporting applications in functional agriculture and the production of bioactive-rich plant materials [35].

Solvent selection critically influences the extraction of antioxidant compounds from rosemary leaves. Total phenolic, flavonoid, and tannin contents, as well as antioxidant activity, varied with the solvent used. Ethanol extracts had the highest phenolic and flavonoid contents, aqueous extracts were richest in tannins, and methanol extracts showed the strongest radical scavenging activity. Strong correlations between phytochemical content and antioxidant activity indicate that solvent choice is key to maximizing the recovery of bioactive antioxidants from rosemary [36, 37].

Anti-inflammatory effect of Rosemary: Rosemary exhibits notable anti-inflammatory activity, in addition to its well-known antioxidant properties. Steam-distilled REO contains eucalyptol (34.25%), α-pinene (20.98%), and camphor (13.75%), with monoterpenes comprising 94.88% of the oil. The oil significantly inhibited protein denaturation in vitro, comparable to the standard drug diclofenac sodium, suggesting that α-pinene and eucalyptol contribute to its anti-inflammatory effects [38].

Aqueous extracts of rosemary have also demonstrated significant anti-inflammatory activity, with an IC50 of 55.88 ± 1.02% in protein-based assays. While the REO and methanolic extracts display other pharmacological activities, the aqueous extract specifically mediates anti-inflammatory effects, supporting its potential as a natural therapeutic agent [39]. In animal studies, co-treatment with aqueous RE mitigated fructose-induced inflammation in rats, reducing inflammatory proteins such as TNF-alpha, interleukin-6, and STAT3, while improving insulin sensitivity and lowering blood glucose levels [40].

Major diterpenes in rosemary, including carnosic acid and carnosol, provide potent anti-inflammatory effects. Their phenolic structures allow direct scavenging of reactive oxygen species and indirect activation of cellular antioxidant defenses. They modulate key inflammatory pathways, including NF-κB, MAPK, Nrf2, SIRT1, STAT3, and NLRP3 inflammasomes, leading to downregulation of pro-inflammatory cytokines, chemokines, adhesion molecules, and prostaglandins. These mechanisms link the antioxidant and anti-inflammatory activities of rosemary, highlighting its therapeutic potential in inflammation-related disorders [41].

However, a randomized clinical trial in women undergoing endotracheal intubation found that topical RE did not significantly reduce sore throat or voice changes compared with a control, suggesting limited efficacy in this specific context [42].

Neuroprotective Effect of Rosemary: Rosemary is a medicinal plant rich in bioactive compounds, including polyphenols such as rosmarinic acid and carnosic acid, as well as flavonoids, tannins, saponins, mucilage, and essential oils. These compounds confer potent antioxidant, anti-inflammatory, and neuroprotective effects, making rosemary a promising natural agent for preserving brain function and promoting healthy longevity [43].

In experimental models of attention deficit hyperactivity disorder, rosemary improved behavioral outcomes, restored antioxidant balance, reduced neuroinflammation, and attenuated neuronal apoptosis in the prefrontal cortex, demonstrating its ability to mitigate ADHD-like neurobehavioral alterations [43]. Its neuroprotective effects extend to heavy metal- and pesticide-induced neurotoxicity, where RE restored brain antioxidant status, modulated neuro-related microRNAs, and reduced oxidative stress and inflammation [44].

Methanolic and essential oil extracts of rosemary exhibit antibacterial and antioxidant activity, that supports neuroprotection by oxidative stress, inflammation, and neuronal apoptosis [45, 46]. Aromatherapy with REO may further enhance limbic system activity and neurotransmission, suggesting neuroprotective effects via olfactory-mediated and systemic mechanisms [47].

Rosemary supports healthy brain aging by reducing oxidative stress, inflammation, and neuronal damage, thereby maintaining cognitive and functional health [48]. Its compounds, including rosmarinic acid, carnosic acid, and carnosol, show therapeutic potential in neurodegenerative disorders such as Alzheimer’s and Parkinson’s disease by reducing neuronal apoptosis, enhancing neurogenesis, and improving antioxidant defenses [49, 50].

In models of diabetic neuropathy, RE improved hyperglycemia, reduced pain sensitivity, restored motor coordination, and suppressed apoptosis markers in spinal cord tissue [51]. In ischemic stroke models, rosemary and carnosic acid reduced infarct volume, improved neurological function, and modulated signaling pathways related to apoptosis, inflammation, and vascular repair [52]. In aged rats, RE protected the prefrontal cortex by improving neuronal integrity, myelin content, and antioxidant enzyme activity, while reducing lipid peroxidation [53].

Rosemary is rich in bioactive compounds, including carnosic acid, carnosol, and rosmarinic acid, which confer antioxidant, anti-inflammatory, and neuroprotective properties. Its RE and REOs are used as flavoring agents and natural preservatives, enhancing antioxidant enzyme levels and providing health-promoting effects. These characteristics make rosemary a valuable resource for food, pharmaceutical, and therapeutic applications [54, 55]. Rosemary also modulates intercellular communication via connexin 43, enhancing cell viability and metabolic activity in neuron-like and glial-like cells under stress, suggesting a role in preventing neurodegeneration [56]. Rosemary is traditionally used for neurological conditions such as headaches, insomnia, and emotional disturbances. Studies show its neuroprotective effects, largely due to antioxidant, anti-inflammatory, and anti-apoptotic activities. Key constituents—carnosic acid, rosmarinic acid, and essential oils—improve memory, reduce neuronal damage, and alleviate anxiety and depression in preclinical models. These properties make rosemary a promising candidate for developing neuroprotective therapeutics with minimal side effects. [57].

Cardiovascular effect of Rosemary: Cardiovascular diseases remain a leading cause of mortality worldwide, and despite advances in pharmacological treatments, many conventional therapies carry adverse effects, prompting interest in safer, plant-derived alternatives. Rosemary, long valued in traditional medicine, exhibits antioxidant, anti-inflammatory, vasorelaxant, and cardioprotective properties, largely attributed to bioactive compounds such as rosmarinic acid, carnosic acid, ursolic acid, and flavonoids [58].

Mechanistic studies show that RE potentiates vascular KCNQ4 and KCNQ5 potassium channels, inducing membrane hyperpolarization and vasorelaxation, with diterpenes carnosol and carnosic acid as key mediators. These effects may vary with sex and hormonal status [59, 60]. In experimental myocardial infarction models, rosemary-derived flavonoids modulate calcium homeostasis and prolyl glycosidase activity, improving cardiac outcomes [61].

RE also selectively inhibits COX-2 in lipopolysaccharide-stimulated macrophages without affecting COX-1 or thromboxane B2, indicating vascular safety alongside anti-inflammatory benefits [62]. Carnosol further exerts cardioprotective effects in pressure-overload models by reducing myocardial hypertrophy, fibrosis, and cardiac dysfunction through activation of the Sirt1/PI3K/AKT pathway. This action helps prevent structural and electrical remodeling, potentially lowering the risk of heart failure and ventricular arrhythmias [63, 64].

Antitumor activity of Rosemary: Rosemary essential oils (REOs) show anticancer potential, primarily due to bioactive compounds such as rosmarinic acid, carnosic acid, and carnosol, which induce apoptosis in various cancer cell lines via both intrinsic and extrinsic pathways. These compounds also inhibit tumor cell proliferation by interfering with cell cycle progression and demonstrate anti-angiogenic effects by suppressing the formation of new blood vessels required for tumor growth. Their antioxidant activity further modulates oxidative stress, which is typically elevated in cancerous tissues, contributing to chemopreventive effects [65].

Positron emission tomography with the thymidine analog tracer [18F]FLT was used to assess the effects of rosmarinic acid in a 4T1 mammary carcinoma Balb/c mouse model. Daily treatment for 21 days significantly reduced [18F]FLT uptake in lung metastases, indicating decreased tumor cell proliferation. This was accompanied by inhibition of tumor growth, migration, and angiogenesis, as well as reduced mast cell, neutrophil, and macrophage infiltration in tumors and lung tissues. [66].

Rosemary extracts (REs) show antitumor activity, largely attributed to carnosic acid, carnosol, ursolic acid, and rosmarinic acid. Beyond antioxidant effects, they act through multiple molecular pathways. Safe for human use as food antioxidants, REs hold promises as complementary cancer therapies, with whole extracts potentially more effective than isolated compounds. [67, 68].

Carnosic acid induces cancer cell death through ROS elevation, AKT inhibition, and mitochondrial disruption, while rosmarinic acid triggers apoptosis, cell cycle arrest, and anti-angiogenic effects. Both compounds may also modulate tumor-related inflammation via interactions with cancer- and inflammation-associated proteins [69, 70].

In breast cancer, particularly triple-negative breast cancer resistant to hormone therapy, rosmarinic acid has shown chemoprotective and anticancer effects by modulating key signaling pathways and activating endogenous defense mechanisms [71]. Hepatocellular carcinoma studies demonstrate that rosemary and saffron induce apoptosis, activate AMPK, suppress colony formation, and inhibit oncogenic pathways including NF-κB, STAT3, JAK1/2, and Akt/mTOR, while reducing VEGF expression, highlighting antiangiogenic effects [72].

Carnosol, a key rosemary diterpene, exhibits antitumor and anti-inflammatory effects. HPLC-QTOF-MS/MS and virtual screening identified targets such as Hsp90α, AKR1C3, and Hsp90β, implicating IL-17, TNF, and Th17 signaling pathways [73].

Rosemary shows antitumor effects by inducing cytotoxicity, modulating signaling, and boosting immunity. Liposomal extracts reduced colorectal tumor size, increased Bax and IFN-γ, enhanced T-cell infiltration, and suppressed Bcl-2 without harming normal splenocytes [74]. REOs selectively inhibited liver cancer cell proliferation via downregulation of Ki-67, beta-catenin, and c-myc [75], while solid lipid nanoparticle formulations decreased tumor size, mortality, and pro-inflammatory cytokines in Ehrlich carcinoma-bearing mice [76, 77]. Extracts rich in caffeic acid and naringenin demonstrated strong cytotoxicity against colon and prostate cancer cells [78], and rosmarinic acid broadly suppressed proliferation, induced apoptosis, and prevented metastasis [79].

Rosemary leaf ethanol extract preserved tumor suppressor p53 in hepatocellular carcinoma models [80, 81], and polyphenols effectively targeted oxidative stress and inflammatory pathways across cancer types [82]. Methanolic extracts selectively inhibited triple-negative and estrogen receptor-positive breast cancer cell lines while sparing normal cartilage cells [83]. Combinations with saffron enhanced efficacy in hepatocellular carcinoma via suppression of NF-κB, STAT3, JAK/Akt/mTOR pathways and angiogenesis [84].

Antidiabetic and hepatoprotective activities of Rosemary: Rosemary exhibits notable antidiabetic and hepatoprotective effects through its antioxidant, anti-inflammatory, and metabolic-regulating properties. In experimental models, RE prevented oxidative liver damage, preserved normal liver enzyme levels, and improved biochemical markers of glucose metabolism and oxidative stress [85]. Dietary supplementation with rosemary leaf powder reduced blood glucose in streptozotocin-induced diabetic rats, improved liver function, and favorably modulated lipid profiles by lowering alanine aminotransferase, aspartate aminotransferase, bilirubin, creatinine, triglycerides, total cholesterol, and LDL, while increasing HDL levels [86, 87].

REO demonstrated nephroprotective effects in diabetic rats by reducing oxidative stress, inflammation, and kidney tissue injury. Combined administration with insulin restored normal glycemia, kidney function, and antioxidant status [88]. Given the rising prevalence of type 2 diabetes and limitations of conventional therapies—such as side effects, high costs, and poor adherence—bioactive compounds in rosemary, including terpenoids, polyphenols, and flavonoids, have gained attention as functional food ingredients to support metabolic health [88, 89].

These findings collectively highlight rosemary as a multifunctional natural agent capable of supporting liver, kidney, and metabolic health in diabetes.

Rosemary as a Functional Food: Rosemary, a member of the Lamiaceae family, is both an attractive horticultural plant and a valuable agricultural crop. It's essential oil has long been prized worldwide and is increasingly recognized as a promising functional food additive with notable health benefits. Due to its distinctive aroma, flavor, and nutritional value, rosemary plays an important role in the food and feed industries, including applications in food packaging. Its unique phytochemical profile, rich in bioactive compounds, underlies diverse health-promoting properties and supports the prevention and management of various conditions [90].

Concerns over the toxicological and carcinogenic effects of artificial preservatives in the meat industry, combined with growing demand for natural alternatives, have highlighted rosemary as one of the most promising candidates. Rosemary reduces oxidative reactions and inhibits microbial growth in meat products, extending shelf life. Its beneficial biological properties—antioxidant, antimicrobial, anti-inflammatory, anticancer, and neuroprotective—are primarily attributed to phenolic diterpenes, flavonoids, and triterpenes. Applications include direct incorporation into foods, active packaging systems, and encapsulation strategies to enhance stability and efficacy [91].

Rosemary bioactive compounds also exert antidiabetic, antifungal, and neuroprotective effects, and contribute to improved fasting blood glucose, vitamin B12 levels, oxidative stress reduction, and cognitive function. These types of health claims are subject to the regulatory frameworks examined in comparative analyses between the U.S. and Japan, such as Functional Foods for Cholesterol Management: A Comparison between the United States and Japan which discusses how functional foods are validated, labeled, and accepted in different jurisdictions [92]. Rosmarinic acid, for example, is widely used in dairy products to prevent lipid oxidation and extend shelf life. Research on extraction methods, therapeutic potential, and industrial applications highlights rosemary's versatility across pharmacology, home cooking, cosmetics, and the food industry [93].

As a functional food, rosemary exemplifies the delivery of health benefits beyond basic nutrition. Its polyphenols, flavonoids, and terpenes support metabolic regulation, immune function, and reduction of risk factors for chronic diseases, including cardiovascular disorders, diabetes, and cancer. Incorporation into foods enhances sensory qualities while providing bioactive compounds in a dietary context. Advances in functional food science emphasize understanding bioavailability, mechanisms of action, safety, and optimization of extraction, stabilization, and delivery methods, such as encapsulation. Importantly, alignment with GRAS status requirements is also a necessary step in functional food development, as outlined by Son and Martirosyan in Salient Features for GRAS Status Affirmation [94]. By integrating food technology, nutrition, and biomedical research, rosemary serves as a model functional food ingredient with potential applications in disease prevention and health maintenance [95] [95].

Evaluation against the FFC Functional Food Model To align with the Functional Food Center (FFC) framework, rosemary's applications can be evaluated across the sequential steps of functional food development. Several steps are already fulfilled: rosemary's major bioactive compounds (rosmarinic acid, carnosic acid, carnosol) are well identified and chemically characterized; proposed quality markers (Q-markers) exist; and numerous studies demonstrate successful incorporation into foods, encapsulation systems, and active packaging. However, other steps remain incomplete. Comprehensive GRAS assessments for standardized rosemary extracts are limited, bioavailability and food-matrix stability data are scarce, and robust, replicated human clinical trials are lacking. In addition, regulatory approval and labeling frameworks for rosemary-based functional food ingredients have yet to be fully established. Therefore, rosemary is advanced in terms of phytochemical characterization and technological applications, but requires further progress in safety validation, standardization, clinical efficacy, and regulatory acceptance to completely meet the FFC functional food model.

CONCLUSION

Rosemary is one of the most promising medicinal and aromatic plants, with a long history of traditional use and a growing body of modern scientific evidence. Its rich phytochemical profile—including diterpenes such as carnosic acid and carnosol, phenolic acids such as rosmarinic acid, and volatile terpenes including 1,8-cineole and α-pinene—underlies a wide spectrum of biological effects. These compounds exhibit potent antioxidant, anti-inflammatory, antimicrobial, antitumor, neuroprotective, cardioprotective, hepatoprotective, and antidiabetic activities, highlighting rosemary's multifunctional therapeutic potential.

Beyond pharmacological effects, rosemary is increasingly valued as a functional food ingredient and natural preservative. Its inclusion in food systems enhances oxidative stability, extends shelf life, and delivers bioactive compounds that support health, bridging nutrition and medicine and aligning with preventive strategies against chronic diseases.

Despite these advantages, challenges remain. Variability in chemical composition complicates standardization, and well-designed clinical trials are still limited. Questions of bioavailability, optimal dosage, and long-term safety also require further investigation.

Future research should focus on developing standardized REs with defined quality markers, improving delivery systems such as encapsulation and nanotechnology to enhance bioavailability, and conducting rigorous clinical trials to validate efficacy in humans. Such advances will strengthen rosemary's role as a therapeutic agent and expand its applications in functional foods, nutraceuticals, and pharmaceuticals.

In conclusion, rosemary embodies the convergence of traditional herbal wisdom and modern functional food science. Its unique phytochemical composition, diverse health-promoting properties, and versatile applications highlight its potential to contribute significantly to chronic disease prevention, health maintenance, and innovative food development. With continued research and technological innovation, rosemary may evolve from a culinary herb into a cornerstone of future functional nutrition and natural therapeutics.

Abbreviations: National Academy of Sciences of the Republic of Armenia - NAS RA; GC–MS - Gas Chromatography–Mass Spectrometry; GC–FID - Gas Chromatography–Flame Ionization Detection; PEF-RO - Pulsed Electric Field–RE; HUP-MHD - Hydroalcoholic Ultrasonic Process–Moist Heat-Dried; DPPH - 2,2-Diphenyl-1-picrylhydrazyl; FRAP - Ferric Reducing Antioxidant Power; LC-MS - Liquid Chromatography–Mass Spectrometry; SOD - Superoxide Dismutase; GPx -

Glutathione Peroxidase; NF-kB - Nuclear Factor Kappa B; MAPK - Mitogen-Activated Protein Kinase; STAT3 - Signal Transducer and Activator of Transcription 3; NLRP - NOD-, LRR- and Pyrin domain-containing protein; IL-1β - Interleukin-1 beta; IL-6 - Interleukin-6; TNF -α - Tumor Necrosis Factor alpha; AKT/mTOR - Protein Kinase B / Mechanistic Target of Rapamycin; ADHD - Attention Deficit Hyperactivity Disorder; KCNQ4/5 - Potassium Voltage-Gated Channel Subfamily Q Members 4 and 5; COX-2 - Cyclooxygenase-2;SIRT1/P13K/AKT - Sirtuin 1 / Phosphoinositide 3-Kinase / Protein Kinase B; RE - RE; REO - Rosemary Essential Oil; ABTS - 2,2′-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid); [18F] FLT - 18F-fluoro-3′-deoxy-3′-L-fluorothymidine; JAK1/2 - Janus Kinase 1 and 2; Akt/mTOR - Protein Kinase B / Mechanistic Target of Rapamycin; VEGF - Vascular Endothelial Growth Factor; QTOF-MS/MS - Quadrupole Time-of-Flight Tandem Mass Spectrometry; AKR1C3 - Aldo-Keto Reductase Family 1 Member C3; Hsp90β - Heat Shock Protein 90 beta; Bcl-2 - B-cell Lymphoma 2; Ki-67 - Kiel 67 antigen; LDL - Low-Density Lipoprotein; HDL - High-Density Lipoprotein. GA – conceptualization, supervision, critical revision of the manuscript, writing–review and editing; SS – preparation of the graphical abstract and table; VH – literature review, data organization, writing – original draft preparation; NP – literature search, writing – review and editing; QN – validation, critical analysis, writing – review and editing; MS - literature search, data analysis, GM - writing – review and editing; IG – plant taxonomy and botanical background, writing – review and editing.

Competing Interests: The authors have no financial interests or conflicts of interest. All authors contributed to the drafting of the manuscript, revised it critically for important intellectual content, and approved the final version.

Authors' contribution: All authors contributed to this study.

REFERENCES

1. Panwar S, Kamath SR, Panigrahi S. Rosemary (*Salvia rosmarinus*). In: Edible flowers. 1st ed. London: Academic Press; 2024; 249-70. DOI: https://doi.org/10.1016/B978-0-443-13769-3.00014-5
2. Mateu-Andrés I, Segarra-Moragues JG, González-Candelas F. Geographical patterns of genetic variation in rosemary (*Rosmarinus officinalis*) in the Mediterranean basin. Bot J Linn Soc. 2013;171(4):700-12. DOI: https://doi.org/10.1111/boj.12017
3. Baptista A, Soares S, Silva AMS, Ferreira ICFR, Barros L. Unlocking the hidden potential of rosemary (*Salvia rosmarinus* Spenn.): New insights into phenolics, terpenes, and antioxidants of Mediterranean cultivars. Plants. 2024;13(23):3395. DOI: https://doi.org/10.3390/plants13233395
4. Li Pomi F, Vaccaro S, Scandurra A, Calabrese G, Torrisi MR, et al. *Rosmarinus officinalis* and skin: Antioxidant activity and possible therapeutical role in cutaneous diseases. Antioxidants. 2023; 12(3):680. DOI: https://doi.org/10.3390/antiox12030680
5. Noshirvani N. Essential oils as natural food preservatives: Special emphasis on antimicrobial and antioxidant activities. J Food Qual. 2024; :5807281. DOI: https://doi.org/10.1155/jfq/5807281
6. El Hassani EA, Baraket A, Alem C. Recent advances in natural food preservatives: A sustainable solution for food safety and shelf-life extension. Food Meas. 2025; 19:293-315. DOI: https://doi.org/10.1007/s11694-024-02969-x
7. Meziane H, Mahdad S, Ouchenane S, Touil A, Chentoufi T, et al. *Rosmarinus officinalis* Linn.: Unveiling its multifaceted nature in nutrition, diverse applications, and advanced extraction methods. J Umm Al-Qura Univ Appl Sci. 2025; 11(1):9-37. DOI: https://doi.org/10.1007/s43994-024-00144-y
8. Shariatmadari F, Ahmadi H. An overview of rosemary in modern poultry nutrition and production. Worlds Poult Sci J. 2025; 81(1):1-15. DOI: https://doi.org/10.1080/00439339.2025.2507827
9. Benyaich A, Aksissou M. The pharmacological and nutritional properties of *Rosmarinus officinalis*: A comprehensive review. Trop J Nat Prod Res. 2024; 8(11). Available from: https://www.researchgate.net/publication/386372654
10. Martirosyan D. Functional foods and mental health. In: Functional Food Science – Textbook Series. Vol. 7. 1st ed. Dallas: Food Science Publisher; 2021.

11. Naghibi F, Mosaddegh M, Motamed SM, Ghorbani A. Labiatae family in folk medicine in Iran: From ethnobotany to pharmacology. Iran J Pharm Res. 2010; 9(1):63-79. DOI: https://doi.org/10.22037/ijpr.2010.619
12. Raja RR. Medicinally potential plants of Labiatae (Lamiaceae) family: An overview. Res J Med Plant. 2012; 6(3):203-13. DOI: https://doi.org/10.3923/rjmp.2012.203.213
13. Wagstaff SJ, Hickerson L, Spangler R, Reeves PA, Olmstead RG. Phylogeny in Labiatae s.l. inferred from cpDNA sequences. Plant Syst Evol. 1998; 209(3-4):265-74. DOI: https://doi.org/10.1007/BF00985232
14. Al-Sereiti MR, Abu-Amer KM, Sen P. Pharmacology of rosemary (*Rosmarinus officinalis* Linn.) and its therapeutic potentials. Indian J Exp Biol. 1999; 37(2):124-30. PMID: 10641130
15. World Health Organization. WHO monographs on selected medicinal plants. Vol. 1. Geneva: WHO; 2003.
16. Begu A, Sandhya S, Ali SS, Vinod KR, Reddy S, Banji D. An in-depth review on the medicinal flora *Rosmarinus officinalis* (Lamiaceae). Acta Sci Pol Technol Aliment. 2013; 12(1):61-73. PMID: 24584866
17. Comissão Permanente da Farmacopeia Portuguesa. Farmacopeia Portuguesa. 7th ed. Lisbon: Ministério da Saúde; 2003.
18. Oualdi I, Sebei K, Msaada K, Hosni K, Brahim AH, Marzouk B. *Rosmarinus officinalis* from Morocco, Italy and France: Insight into chemical compositions and biological properties. Mater Today Proc. 2021; 45:7706-10. DOI: https://doi.org/10.1016/j.matpr.2021.03.333
19. Shen X, Zhou M, Zhu X, Zhang J, Xu J, Jiang W. Chemical composition and antioxidant activity of petroleum ether fraction of *Rosmarinus officinalis*. Heliyon. 2023; 9(11): e21316. DOI: https://doi.org/10.1016/j.heliyon.2023.e21316
20. Chen F, Su X, Yan T, Fu X, Wang J, Luo D, et al. Homogenate-ultrasonic pretreatment followed by microwave hydrodistillation of essential oil from rosemary (*Rosmarinus officinalis* L.) leaves: Kinetic, chemical composition, and biological activity. Sustain Chem Pharm. 2024; 42:101744. DOI: https://doi.org/10.1016/j.scp.2024.101744
21. Bejenaru LE, Segneanu AE, Bejenaru C, Biţă A, Tuţulescu F, Radu A, et al. Seasonal variations in chemical composition and antibacterial and antioxidant activities of *Rosmarinus officinalis* L. essential oil from Southwestern Romania. Appl Sci. 2025; 15(2):681-700. DOI: https://doi.org/10.3390/app15020681
22. Lin X, Huang Y, Chen J, Zhang R, Li C. A mini-review on the chemical composition, extraction and isolation techniques, and pharmacological activity of *Rosmarinus officinalis* L. Curr Chin Sci. 2024; 4(2):85-94. DOI: https://doi.org/10.2174/0122102981258712231114073051
23. Li T, Tang Z, Zhu J, Ye C, Xu H, Ge W, et al. Predictive analysis of *Rosmarinus officinalis* L. quality marker (Q-marker) based on chemical composition, activity and network pharmacology. Curr Anal Chem. 2025. DOI: https://doi.org/10.2174/0115734110367575250418100500
24. Rafya M, Zehhar N, Hafidi A, Benkhalti F. Review of *Rosmarinus officinalis* L. essential oil, hydrosol, and residues analysis: Composition, bioactivities, and valorization. Ind Crops Prod. 2024; 221:119392. DOI: https://doi.org/10.1016/j.indcrop.2024.119392
25. Laftouhi A, Mahraz M, Hmamou A, Assougeum A, Ullah R, Bari A, et al. Analysis of primary and secondary metabolites, physical properties, antioxidant and antidiabetic activities, and chemical composition of *Rosmarinus officinalis* essential oils under differential water stress conditions. ACS Omega. 2024; 9(14):16656-64. DOI: https://doi.org/10.1021/acsomega.4c00653
26. Oualdi I, Diass K, Azizi S, Dalli M, Touzani R, Gseyra N, et al. *Rosmarinus officinalis* essential oils from Morocco: New advances on extraction, GC/MS analysis, and antioxidant activity. Nat Prod Res. 2023; 37(12):2003-8. DOI: https://doi.org/10.1080/14786419.2022.2111561
27. Hcini K, Bahi A, Abidi M, Zarroug M, Kahlaoui S, Quilez M, et al. Chemical composition and biological activities of Tunisian wild rosemary (*Rosmarinus officinalis* L.) essential oils. Novel Asp Chem Biochem. 2023; 6B:17-44. DOI: https://doi.org/10.9734/bpi/nacb/v6/6217A
28. Francolino R, Martino M, Caputo L, Amato G, Chianese G, Gargiulo E, et al. Phytochemical constituents and biological activity of wild and cultivated *Rosmarinus officinalis* hydroalcoholic extracts. Antioxidants. 2023; 12(8):1633. DOI: https://doi.org/10.3390/antiox12081633
29. Singh PK, Singh N, Chopra R, Garg M, Chand M, Dhiman A, et al. Rosemary bioactives as antioxidant agents: A bidirectional approach to improving human health and vegetable oil stability. Food Chem Adv. 2025; 7:100952. DOI: https://doi.org/10.1016/j.focha.2025.100952
30. Wang P, Wei Q, Zhang C, Pan H, Li J, Ji P, et al. Effect of rosemary on growth performance, meat quality, fatty acid content, intestinal flora, and antioxidant capacity of broilers. Animals (Basel). 2024; 14(17):2480. DOI: https://doi.org/10.3390/ani14172480
31. Sahlabgi A, Lupuliasa D, Stanciu G, Lupşor S, Vlaia LL, Rotariu R, et al. The development and comparative evaluation of rosemary hydroalcoholic macerate-based dermatocosmetic

preparations: A study on antioxidant, antimicrobial, and anti-inflammatory properties. Gels. 2025; 11(3):149. DOI: https://doi.org/10.3390/gels11030149

32. Teja YS, Jyothhika L, Vasavi N, Reddy K, Sudheer A. Exploring the therapeutic potential of rosemary: An in-depth review of its pharmacological properties. Asian J Adv Med Sci. 2024; 6(1):19-31. Available from: https://journalmedicals.com/index.php/AJOAIMS/article/view/141
33. Kompelly A, Kompelly S, Vasudha B, Narender B. *Rosmarinus officinalis* L.: An update review of its phytochemistry and biological activity. J Drug Deliv Ther. 2019; 9(1):323-30. DOI: https://doi.org/10.22270/jddt.v9i1.2218
34. Bakri M, Alghonaim M, Alsalamah S, Yahya R, Ismail K, Abdelghany T. Impact of moist heat on phytochemical constituents, anti-*Helicobacter pylori*, antioxidant, antidiabetic, hemolytic and healing properties of rosemary plant extract in vitro. Waste Biomass Valor. 2024; 15:4965-79. DOI: https://doi.org/10.1007/s12649-024-02490-8
35. Park J, Seo JW, Ham DY, Choi HJ, Kim MJ, Na JK, et al. Antioxidant activity and phenolic compounds of rosemary under artificial LED lights. Agronomy. 2025; 15(3):636. DOI: https://doi.org/10.3390/agronomy15030636
36. Al-jaafreh AM. Evaluation of antioxidant activities of rosemary (*Rosmarinus officinalis* L.) essential oil and different types of solvent extractions. Biomed Pharmacol J. 2024; 17(1):323-39. DOI: https://doi.org/10.13005/bpj/2860
37. Jahanfar S, Gahavami M, Khosravi K, Jahadi M, Mohsin H, Todorov D, et al. The effect of antioxidant properties of free and encapsulated RE in liposome on the oxidation process of canola oil. Int J Food Sci Technol. 2023; 58(10):5521-9. DOI: https://doi.org/10.1111/ijfs.16450
38. Khalil DY, Hassan OM. Anti-inflammatory and antioxidant activity of rosemary essential oil. J Angiotherapy. 2024; 8(4):1-6. DOI: https://doi.org/10.25163/angiotherapy.849609
39. Mahboub N, Cherfi I, Laouini S, Bouafia A, Benaissa A, Alia K, et al. GC/MS and LC composition analysis of essential oil and extracts from wild rosemary: Evaluation of their antioxidant, antimicrobial, and anti-inflammatory activities. Biomed Chromatogr. 2025; 39(5):e70084. DOI: https://doi.org/10.1002/bmc.70084
40. Issa W, Masudb A. The effect of treatment with fructose on some biochemical and immune variables and the protective roles of RE against these effects in male rats. Ibn Sina J Med Sci Health Pharm. 2025; 2(1):1-8. https://ibn-sina-journal-of-medical-sciences.jo
41. Habtemariam S. Anti-inflammatory therapeutic mechanisms of natural products: Insight from rosemary diterpenes, carnosic acid and carnosol. Biomedicines. 2023; 11(2):545. DOI: https://doi.org/10.3390/biomedicines11020545
42. Mallah F, Dehghani A. Evaluation of anti-inflammatory effects of RE in reducing the need for dexamethasone in intubation: A randomized clinical trial. Int J Med Invest. 2021;10(3):3-12. DOR: 20.1001.1.23222913.2021.10.3.15.3]
43. Abdelrazik E, Hassan H, Hamza E, Ezz Elregal F, Elnagdy M, Abdulhai E. Beneficial role of RE on oxidative stress-mediated neuronal apoptosis in rotenone-induced attention deficit hyperactivity disease in juvenile rat model. Acta Biomed. 2023; 94(3): e2023104. DOI: https://doi.org/10.23750/abm.v94i3.14260
44. Hussein A, Senosi Y, Mahfouz M, Arafa M, Hassan M. Epigenetic impact and ameliorative potential role of quercetin or RE on metalaxyl or manganese chloride-induced toxicity via mitigation of microRNA, DNA methylation and regulation of MAPK phosphorylation in rats. J Adv Vet Res. 2024; 14(7):1160-7. Available from: https://advetresearch.com/index.php/AVR/article/view/2000
45. Rana M, Jamous I, Salam Y, Abu Z, Ali-Shtayeh M. Ethnobotanical perspectives on natural acetylcholinesterase inhibitors: Towards alternative approaches to Alzheimer’s disease. Biodivers Environ Sci Stud Ser. 2024; 19(1).
46. Abd-Elhak N, Abd El-Rahman, Hashem M. Fennel, carob, REs as anti-inflammatory activity functions on formalin-induced paw edema in albino rats. Food Technol Res J. 2024; 3(1):14-32. DOI: https://doi.org/10.21608/ftrj.2024.341747
47. Merkulova E. Aromatherapy: A novel approach to schizophrenia treatment. In: Aromatherapy: A novel approach to schizophrenia treatment. 1st ed. Cambridge: RSC Publishing; 2024; 133-55. DOI: https://doi.org/10.1039/9781837672059-00133
48. Prasad P, Mathew A, Jose S, Akbarsh MA, Panicker SP. Fostering healthy longevity through regenerative and precision medicine: Biodiversity’s vital role and equitable benefit sharing. In: Panicker LK, Nelliyat P, Oommen OV, editors. Biodiversity and business. Cham: Springer; 2024; p. 1-27. DOI: https://doi.org/10.1007/978-3-031-71674-4_27
49. Kosmopoulou D, Lafara MP, Adamantidi T, Ofrydopoulou A, Grabrucker AM, Tsoupras A. Neuroprotective benefits of *Rosmarinus officinalis* and its bioactives against Alzheimer’s and Parkinson’s diseases. Appl Sci. 2024; 14(15):6417. DOI: https://doi.org/10.3390/app14156417

50. Faridzadeh A, Salimi Y, Ghasemirad H, Hargar M, Rashtchian A, Deravi N, et al. Neuroprotective potential of aromatic herbs: Rosemary, sage, and lavender. Front Neurosci. 2022; 16:909833.
DOI: https://doi.org/10.3389/fnins.2022.909833
51. Rasoulian B, Hajializadeh Z, Esmaeili-Mahani S, Rashidipour M, Fatemi I, Kaeidi A. Neuroprotective and antinociceptive effects of rosemary (*Rosmarinus officinalis* L.) extract in rats with painful diabetic neuropathy. J Physiol Sci. 2019; 69(1):57-64.
DOI: https://doi.org/10.1007/s12576-018-0620-x
52. Li W, Liu C, Xu C, Hang H, Meng Y, Zhao H, et al. Differential neuroprotective mechanisms of rosemary and carnosic acid in cerebral ischemia-reperfusion injury. Neurol Res. 2025; 1-14. DOI: https://doi.org/10.1080/01616412.2025.2520014
53. Eslami Farsani M, Razavi S, Rasoolijazi H, Esfandiary E, Seyedebrahimi R, Ababzadeh S. Neuroprotective effects of RE on white matter of prefrontal cortex in old rats. Iran J Basic Med Sci. 2024; 27(4):518-23.
DOI: https://doi.org/10.22038/ijbms.2023.74168.16117
54. Aziz E, Batool R, Akhtar W, Shahzad T, Malik A, Shah MA, et al. Rosemary species: A review of phytochemicals, bioactivities and industrial applications. S Afr J Bot. 2022; 151:3-18. DOI: https://doi.org/10.1016/j.sajb.2021.09.026
55. Mirza F, Zahid S, Holsinger R. Neuroprotective effects of carnosic acid: Insight into its mechanisms of action. Molecules. 2023; 28(5):2306.
DOI: https://doi.org/10.3390/molecules28052306
56. Zappalà A, Vicario N, Calabrese G, Turnaturi R, Pasquinucci L, Montenegro L, et al. Neuroprotective effects of *Rosmarinus officinalis* L. extract in oxygen-glucose deprivation-injured human neural-like cells. Nat Prod Res. 2019; 35(4):669-75.
DOI: https://doi.org/10.1080/14786419.2019.1587428
57. Ghasemzadeh Rahbardar M, Hosseinzadeh H. Therapeutic effects of rosemary (*Rosmarinus officinalis* L.) and its active constituents on nervous system disorders. Iran J Basic Med Sci. 2020; 23(9):1100-12.
DOI: https://doi.org/10.22038/ijbms.2020.45269.10541
58. Liang YC, Wan TJ, Wer TW, Zhang J, Li YF. Potential role of rosemary in cardiovascular disease therapies: Progress and promise. Tradit Med Res. 2025; 10(8):50.
DOI: https://doi.org/10.53388/TMR20241005001
59. Manville R, Baldwin S, Eriksen E, Jepps T, Abbott G. Medicinal plant rosemary relaxes blood vessels by activating vascular smooth muscle KCNQ channels. FASEB J. 2023; 37(9): e23125. DOI: https://doi.org/10.1096/fj.202301132R
60. Merimi C, Benabbou A, Bourassi L, Addous A, Elhenawy AA, Touzani R, et al. In silico evaluation of bioactive compounds (flavonoids, rosmarinic acid) from five plants (rosemary, oregano, pink savory, lemon balm, and saffron) and their role in cardiovascular health and hypertension. OBM Integr Complement Med. 2025; 10(2).
DOI: https://doi.org/10.21926/obm.icm.2502027
61. Harem S, Shaker A. Extraction design of flavonoids from rosemary plants for the treatment of acute myocardial infarction in rats. Macromol Symp. 2025; 414(1).
DOI: https://doi.org/10.1002/masy.202400225
62. Lee S, Park SY, Kim K, Kim S. Evaluation of cyclooxygenase inhibition in RE. J Appl Biol Chem. 2023; 66(2):114-21. DOI: https://doi.org/10.3839/jabc.2023.017
63. Fang Z, Lu M, Huang R, Wang G, Yushanjiang F, Jiang X, et al. Carnosol prevents cardiac remodeling and ventricular arrhythmias in pressure overload-induced heart failure mice. Phytother Res. 2024; 38(7):3763-81.
DOI: https://doi.org/10.1002/ptr.8213
64. Trimarco B, Santulli G. Dietary supplements in cardiovascular and metabolic diseases. Nutrients. 2024; 16(10):1418. DOI: https://doi.org/10.3390/nu16101418
65. Kowalczyk A, Tuberoso CIG, Jerković I. The role of rosmarinic acid in cancer prevention and therapy: Mechanisms of antioxidant and anticancer activity. Antioxidants. 2024; 13(11):1313. DOI: https://doi.org/10.3390/antiox13111313
66. Silva J, Pereira J, Schirmer B, Araujo M, Nascimento L, Ferreira A, et al. Use of 18F-FLT/PET for assessing the tumor evolution and monitoring the antitumor activity of rosmarinic acid in a mouse 4T1 breast tumor model. Braz J Radiat Sci. 2023; 11(3):1-13.
DOI: https://doi.org/10.15392/2319-0612.2023.2300
67. González-Vallinas M, Reglero G, Ramirez de Molina A. Rosemary (*Rosmarinus officinalis* L.) extract as a potential complementary agent in anticancer therapy. Nutr Cancer. 2015; 67(8):1223-31.
DOI: https://doi.org/10.1080/01635581.2015.1082110
68. Singh D, Mittal N, Siddiqui M. A review on pharmacological potentials of phenolic diterpenes carnosic acid and carnosol obtained from *Rosmarinus officinalis* L. and modern extraction methods implicated in their recovery. Trends Phytochem Res. 2023; 7(3):156-69.
DOI: https://doi.org/10.30495/tpr.2023.1990761.1365
69. Bouammali H, Zraibi L, Ziani I, Merzouki M, Bourassi L, Fraj E, et al. Rosemary as a potential source of natural antioxidants and anticancer agents: A molecular docking study. Plants. 2024; 13(1):89.

DOI: https://doi.org/10.3390/plants13010089

70. Chen C, Liu Y, Shen Y, Zhu L, Yao L, Wang X, et al. Rosmarinic acid, the active component of Rubi Fructus, induces apoptosis of SGC-7901 and HepG2 cells through mitochondrial pathway and exerts anti-tumor effect. Naunyn Schmiedebergs Arch Pharmacol. 2023; 396:3743-55. DOI: https://doi.org/10.1007/s00210-023-02552-z
71. Konstantinou EK, Panagiotopoulos AA, Argyri K, Panoutsopoulos GI, Dimitriou M, Gioxari A. Molecular pathways of rosmarinic acid anticancer activity in triple-negative breast cancer cells: A literature review. Nutrients. 2024; 16(1):2. DOI: https://doi.org/10.3390/nu16010002
72. Allegra A, Tonacci A, Pioggia G, Musolino C, Gangemi S. Anticancer activity of *Rosmarinus officinalis* L.: Mechanisms of action and therapeutic potentials. Nutrients. 2020; 12(6):1739. DOI: https://doi.org/10.3390/nu12061739
73. Taboada-Alquerque M, Pajaro-Valenzuela D, Caballero-Gallardo K, Cifuentes A, Ibáñez E, Ahumedo-Monterrosa M, et al. Mapping protein targets of carnosol, a molecule identified in *Rosmarinus officinalis*: In silico docking studies and network pharmacology. Sci Pharm. 2023; 91(2):19. DOI: https://doi.org/10.3390/scipharm91020019
74. Hemmati Bushehri R, Jaafari MR, Mosayebi G, Ghazavi A, Ganji A. Antitumor activity and immunostimulant properties of liposomes containing RE on a mouse model of colorectal cancer. Iran J Immunol. 2024; 21(4):279-93. DOI: https://doi.org/10.22034/iji.2024.103121.2817
75. Becer E, Altundag E, Guran M, Vatansever H, Usturk S, Hanoglu D, et al. Composition and antibacterial, anti-inflammatory, antioxidant, and anticancer activities of *Rosmarinus officinalis* L. essential oil. S Afr J Bot. 2023; 160:437-45. DOI: https://doi.org/10.1016/j.sajb.2023.07.028
76. Elsayed D, Said N, Said A, Hamad H, Abd-Elrazek A. Anticarcinogenic activity of rosemary loaded solid lipid nanoparticle against solid tumor in mice. Labyrinth Fayoum J Sci Interdiscip Stud. 2024; 2(1):8-13. DOI: https://doi.org/10.21608/ifjsis.2024.263353.1056
77. Chetia M, Ashraf G, Sahu R, Nandi G, Karunakaran G, Paul P, et al. Rosemary (*Rosmarinus officinalis* L.) essential oil: A review of extraction technologies and biological activities. Next Res. 2025; 100545. DOI: https://doi.org/10.1016/j.nexres.2025.100545
78. Abo-Elmaaty M, Gedamy G, Taha H, Awad A, El-Maghraby L. Chemical characterization of *Rosmarinus officinalis* L. hydrodistillation by-products, evaluating their antioxidant and anticancer activities. Egypt J Chem. 2025; 68(4):369-79. DOI: https://doi.org/10.21608/ejchem.2024.300267.9951
79. Marcharla E, Anantharaju H, Reddy P, Kumar V, Naik S, Kumar R, et al. Biological properties and anti-cancer potential of nano-formulated rosemary and oregano essential oils against AGS cell line. Food Biosci. 2025; 64:105866. DOI: https://doi.org/10.1016/j.fbio.2025.105866
80. Adnyaswari D, Indrayani A, Artini I, Ernawati D, Trapika G, Sriwidyani N, et al. Effect of rosemary leaf ethanol extract (*Rosmarinus officinalis* L.) on arginase-1 and tumor suppressor P53 expression of hepatocellular carcinoma in male Wistar rats induced by p-dimethylamino benzaldehyde. J Cancer Tumor Int. 2025; 15(1):81-92. DOI: https://doi.org/10.9734/jcti/2025/v15i1285
81. Chammas S, Sanchez J, Alves R, Giovanni L, Maria D. Bioactive compounds of rosemary from the field: a review of the biological effects. Seven Editora. 2023; 831-45. DOI: https://doi.org/10.56238/colleinternhealthscienv1-068
82. Sirajudeen F, Bou Malhab LJ, Bustanji Y, Shahwan M, Alzoubi KH, Semreen MH, et al. Exploring the potential of rosemary-derived compounds (rosmarinic and carnosic acids) as cancer therapeutics: Current knowledge and future perspectives. Biomol Ther (Seoul). 2024; 32(1):38-55. DOI: https://doi.org/10.4062/biomolther.2023.054
83. Darra R, Majdalawieh A, Mahasneh A, Rah B, Hamad M, Kanan S. Anti-proliferative effects of *Rosmarinus officinalis* L. (rosemary) against human breast and liver carcinoma cells. Food Biosci. 2025; 65:106164. DOI: https://doi.org/10.1016/j.fbio.2025.106164
84. Naraki GA, Fazeli Kakhki H, Qoorchi Moheb Seraj F, Naraki K, Ghasemzadeh Rahbardar M. Effect of *Crocus sativus* L. (saffron) and *Rosmarinus officinalis* L. (rosemary) in hepatocellular carcinoma: A narrative review of current evidence and prospects. Iran J Basic Med Sci. 2025; 28(8):986-1003. DOI: https://doi.org/10.22038/ijbms.2025.84172.18204
85. Guimarães N, Ramos V, Prado-Souza L, Lopes R, Arini G, Feitosa L, et al. Rosemary (*Rosmarinus officinalis* L.) glycolic extract protects liver mitochondria from oxidative damage and prevents acetaminophen-induced hepatotoxicity. Antioxidants. 2023; 12(3):628. DOI: https://doi.org/10.3390/antiox12030628
86. Kabubii Z, Mbaria J, Mathiu P, Wanjohi J, Nyaboga E. Diet supplementation with rosemary (*Rosmarinus officinalis* L.) leaf powder exhibits an antidiabetic property in streptozotocin-induced diabetic male Wistar rats. Diabetology. 2024; 5(1):12-25.

DOI: https://doi.org/10.3390/diabetology5010002

87. Theyyathel A, Sofi M, Nanda A, Sofi M, Nayak B. Exploring the therapeutic potential of *Rosmarinus officinalis*: A review study. J Nat Remedies. 2025; 25(1):33-48. DOI: https://doi.org/10.18311/jnr/2025/45190
88. Fareed SA, Yousef EM, Abd El-Moneam SM. Assessment of Effects of Rosemary Essential Oil on the Kidney Pathology of Diabetic Adult Male Albino Rats. Cureus. 2023; 3;15(3):e35736. DOI: https://doi.org/10.7759/cureus.35736
89. Martirosyan D, Christopher S. The benefits of terpenoids as functional foods for the management of type 2 diabetes mellitus. Bioact Comp Health Dis. 2024; 7(7):345-7. DOI: https://doi.org/10.31989/bchd.v7i7.1426
90. Qiu K, Wang S, Duan F, Sang Z, Wei S, Liu H, et al. Rosemary: Unrevealing an old aromatic crop as a new source of promising functional food additive—a review. Compr Rev Food Sci Food Saf. 2024; 23(1): e13273. DOI: https://doi.org/10.1111/1541-4337.13273
91. Kaur R, Gupta TB, Bronlund J, Kaur L. The potential of rosemary as a functional ingredient for meat products: A review. Food Rev Int. 2021; 39(4):2212-23. DOI: https://doi.org/10.1080/87559129.2021.1950173
92. Zhou J., Martirosyan D. Functional foods for cholesterol management: A comparison between the United States and Japan //Functional Food Science-Online ISSN: 2767-3146. – 2024; 4(6). – 228-250.
93. Shankar A, Abid A, Hafiz A, Balaji J, Kaur J, Saeed F, et al. Nutritional composition, phytochemical profile, therapeutic potentials, and food applications ofrosemary: A comprehensive review. J Food Compos Anal. 2024; 135:106688. DOI: https://doi.org/10.1016/j.jfca.2024.106688
94. Son J., Martirosyan D. "Salient features for GRAS status affirmation."*Functional Food Science-Online 2024; ISSN: 2767-3146* 4.8 299-308. DOI: https://doi.org/10.31989/ffs.v4i8.1417
95. Martirosyan D. Functional food science and bioactive compounds. Bioact Comp Health Dis. 2025; 8(6):218-29. DOI: https://doi.org/10.31989/bchd.v8i6.1667