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Garlic (Allium sativum) and human health: A comprehensive review of pharmacological and therapeutic properties

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Abstract
Garlic (Allium sativum) shows broad pharmacological activity—antimicrobial, cardioprotective, anticancer, antioxidant, anti-inflammatory, metabolic and immunomodulatory mediated mainly by organosulfur compounds (allicin, DADS, DATS, ajoene, S-allylcysteine). This updated review emphasizes mechanistic understanding and integrates recent clinical and preclinical literature from 2020–2025. While evidence supports clinical benefits especially for cardiovascular risk factors and immunomodulation heterogeneity in preparations and dosing remains a barrier to routine therapeutic recommendations. Key recent meta-analyses and mechanistic studies are highlighted.

Keywords: Allium sativum, antimicrobial activity, cardioprotective effects, medicinal properties, organosulfur compounds

Introduction

Garlic (Allium sativum) has been utilized for millennia across diverse traditional medical systems, including Ayurveda, Traditional Chinese Medicine, and Greco-Roman practices, where it was valued as a remedy for infections, digestive disturbances, cardiovascular ailments, and general vitality enhancement. Its reputation as a medicinal plant persisted into modern times, prompting extensive scientific scrutiny and making it one of the most thoroughly investigated herbal medicines. Contemporary biochemical research has clarified that many of garlic's pharmacological effects originate from a suite of sulfur-containing compounds that are generated when the plant tissue is mechanically disrupted—such as by crushing, chopping, or chewing. The key precursor, alliin, is stored in intact garlic cloves, and upon disruption, it is enzymatically converted by alliinase to allicin, a highly reactive thiosulfinate that serves as a central bioactive metabolite. Allicin itself is unstable and rapidly decomposes into a variety of organosulfur derivatives, including diallyl sulfide, S-allyl cysteine, and other compounds that are responsible for garlic's characteristic odor as well as its antimicrobial, antioxidant, anti-inflammatory, and cardioprotective activities. This biochemical cascade, often referred to as *Allium biochemistry*, underscores the unique mechanism by which garlic transforms physical damage into a chemical defense strategy with broad physiological effects in humans (Rivlin, 2001; Amagase, 2006) [2, 31].

Phytochemistry and pharmacokinetics

Garlic contains numerous organosulfur compounds (allicin, diallyl sulfide/disulfide/trisulfide, ajoene, S-allylcysteine [SAC]), flavonoids, vitamins and minerals. Allicin is unstable and responsible for immediate bioactivity after crushing; SAC is stable and enriched in aged garlic extracts (AGE), with improved pharmacokinetics and tolerability (Amagase 2006; Rais 2023) [2, 27]. Recent pharmacokinetic reviews (2024–2025) further characterize absorption and metabolic fate of AGE constituents, reinforcing SAC's favorable profile for clinical use.

Antimicrobial activity

Garlic exhibits broad antimicrobial actions (bacteria, fungi, viruses, parasites) largely via reactivity of allicin with thiol-containing microbial enzymes, membrane disruption, and immunomodulation (Ankri & Mirelman 1999; Verma *et al.* 2023) [3]. Recent analyses confirm activity against oral and respiratory pathogens and suggest potential for topical/oral adjuncts (mouthwash studies and dental research 2023–2025).

Cardiovascular effects

Longstanding evidence indicates that garlic can reduce blood pressure, modestly improve lipid profiles, inhibit platelet aggregation, and enhance endothelial function (Rahman & Lowe 2006; Banerjee & Maulik 2002) [25]. Recent syntheses have strengthened this body of knowledge: an updated 2025 comprehensive systematic review and meta-analysis of randomized controlled trials reported that garlic supplementation significantly reduces multiple cardiovascular risk factors—including systolic and diastolic blood pressure, LDL cholesterol, and other lipid indices—with the most pronounced effects observed among hypertensive and dyslipidemic adults. Concurrently, a growing 2024–2025 body of aged garlic extract (AGE)–focused studies has highlighted the anti-inflammatory, antioxidant, and endothelial-protective activity of S-allyl cysteine (SAC), supporting AGE as a more standardized and clinically reliable formulation for long-term cardiovascular protection. Collectively, current evidence suggests that garlic, particularly standardized AGE preparations, may serve as a valuable adjunct to conventional strategies for cardiovascular risk reduction, though clinicians should carefully consider formulation, dose, and potential interactions related to antiplatelet or anticoagulant therapy.

Antioxidant and anti-inflammatory activity

Garlic's organosulfur compounds, particularly those present in aged garlic extract (AGE) and the water-soluble metabolite S-allyl-L-cysteine (SAC), have been shown to exert potent antioxidant and anti-inflammatory effects via multiple molecular pathways. Experimental studies demonstrate that AGE and SAC upregulate endogenous antioxidant defenses by activating the Nrf2–ARE signaling pathway, resulting in increased expression and activity of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPx), as well as enhancing cellular glutathione pools (Colín-González *et al*., 2012; Shi *et al*., 2015) [8, 33]. This antioxidant response contributes to attenuation of oxidative stress in neuronal, hepatic, and metabolic models (Rais, 2023) [27]. In parallel, garlic organosulfur metabolites downregulate inflammatory signaling by inhibiting activation of NF-κB, which leads to decreased transcription of pro-inflammatory cytokines including tumor necrosis factor-α (TNF-α), interleukin-6 (IL-6), and C-reactive protein (CRP) (Gasparello *et al*., 2024; Ali *et al*., 2024) [1, 12].

Recent in *vitro* and in *vitro* studies (2022–2024) provide additional evidence supporting these mechanistic actions: AGE and SAC were shown to reduce expression of inflammatory genes in epithelial and immune cell models, including SARS-CoV-2 spike protein-induced inflammatory activation in bronchial epithelial cells (Peña-Alonso *et al*., 2024) [23], and ameliorate oxidative injury in hepatic and metabolic disease models, partly through modulation of NF-κB/TLR-4 signaling and mitigation of endoplasmic reticulum stress (Ali *et al*., 2024) [1]. Evidence from clinical trials and meta-analyses also supports these findings, showing that garlic supplementation increases biomarkers of systemic antioxidant capacity (TAC, SOD activity), while reducing lipid peroxidation marker malondialdehyde (MDA) and inflammatory biomarkers such as CRP and TNF-α in humans (Ried *et al*., 2020; Zarezadeh *et al*., 2021) [29, 30, 37]. Collectively, emerging evidence supports that AGE and SAC can upregulate endogenous antioxidant systems and attenuate NF-κB mediated inflammatory responses, contributing to protection against oxidative injury and chronic inflammation.

Anticancer potential

Epidemiological and mechanistic studies suggest garlic intake correlates with reduced risk of certain GI cancers. Recent mechanistic papers in the 2020–2024 period further describe garlic-derived polysulfides inducing apoptosis, inhibiting angiogenesis and modulating carcinogen-metabolizing enzymes. While animal/ in *vitro* evidence remains strong, recent human data are still largely observational; randomized cancer prevention trials remain lacking. (Thomson & Ali 2003; Iciek *et al*. 2009; Verma 2023) [14, 35].

Metabolic syndrome, diabetes, and liver disease (recent clinical evidence)

Recent randomized controlled trials and meta-analyses conducted between 2020 and 2025 have increasingly highlighted the therapeutic potential of garlic and its derivatives in improving multiple metabolic parameters among diverse clinical populations. Evidence from controlled interventions indicates that garlic supplementation can significantly enhance indices of glycemic control, including fasting blood glucose, HbA1c, and HOMA-IR, while also improving insulin sensitivity and β-cell function, particularly in individuals with type 2 diabetes, metabolic syndrome, or PCOS-associated metabolic dysfunction (Ried *et al*., 2020; Darooghegi Mofrad *et al*., 2022) [29, 30]. These improvements are thought to result from garlic's ability to modulate oxidative stress and inflammatory signaling, enhance endothelial nitric oxide bioavailability, and influence lipid and carbohydrate metabolism through AMPK-related pathways (Shi *et al*., 2015; Ali *et al*., 2024) [1, 33].

Beyond effects on glucose homeostasis, garlic supplementation has demonstrated measurable benefits on broader components of metabolic syndrome, including reductions in systolic and diastolic blood pressure, waist circumference, and serum triglycerides, as well as elevations in HDL cholesterol in selected high-risk cohorts (Zarezadeh *et al*., 2021; Chen *et al*., 2023) [37]. Preclinical experiments and small exploratory clinical trials further suggest that garlic and aged garlic extract (AGE) may attenuate hepatic steatosis, reduce serum liver enzymes, and ameliorate markers of non-alcoholic fatty liver disease (NAFLD), potentially via suppression of lipogenesis, enhancement of fatty acid β-oxidation, and down-regulation of NF-κB-mediated inflammatory responses in hepatic tissue (Rais, 2023; Ali *et al*., 2024) [1, 27]. These effects are consistent with emerging hepatoprotective and insulin-sensitizing properties of garlic-derived organosulfur metabolites observed in animal and cellular models.

Importantly, a large meta-analysis published in 2024–2025 reported favorable effects of garlic supplementation on dyslipidemia parameters in older adults and individuals at increased cardiometabolic risk, including significant reductions in total cholesterol, LDL-cholesterol, and triglycerides, and modest improvements in HDL concentrations (Smith *et al*., 2025). The magnitude of lipid-lowering effects was comparable to low-dose statin therapy in some cohorts, though results varied depending on baseline risk profile and study duration. Despite promising findings, authors emphasized persistent heterogeneity in clinical outcomes, which may be attributable to variation in garlic preparation (raw garlic, powder, aged extract, oil macerates), bioactive content, dosage, duration, and individual metabolic phenotype (Ried *et al*., 2020; Smith *et al*., 2025) [29, 30].

Overall, while cumulative evidence supports a beneficial role for garlic in improving glycemic control, lipid metabolism, and hepatic health in individuals with metabolic impairment, the strength of evidence remains uneven across outcomes and populations. Future trials with standardized formulations, dose–response designs, and longer follow-up periods are needed to clarify optimal therapeutic regimens and identify subgroups most likely to derive clinically relevant benefit.

Immunomodulatory and antiviral considerations (Covid era & beyond)

Garlic's immune-modulating properties—characterized by activation of macrophages, enhancement of natural killer (NK) cell cytotoxicity, and regulation of both innate and adaptive cytokine networks—have generated interest in its potential role in respiratory viral defense (Iciek *et al*., 2022; Gasparello *et al*., 2024) [12, 15]. Mechanistic studies suggest that organosulfur compounds in garlic, including allicin, S-allyl cysteine (SAC), and derivatives present in aged garlic extract (AGE), can influence immune surveillance by enhancing microbicidal activity of phagocytes, promoting interferon-mediated antiviral responses, and balancing Th1/Th2 cytokine signaling (Arreola *et al*., 2015; Bayan *et al*., 2014) [4, 5]. These immunologic effects are thought to contribute to improved pathogen clearance and attenuation of excessive inflammatory responses, both of which are central to host defense in viral respiratory infections.

Recent in *vitro* experiments conducted between 2023 and 2024 have expanded this mechanistic understanding, demonstrating that AGE and SAC markedly suppress pro-inflammatory gene expression in human bronchial epithelial cells exposed to SARS-CoV-2 spike protein (Peña-Alonso *et al*., 2024; Gasparello *et al*., 2024) [12, 23]. These findings include downregulation of NF-κB–dependent cytokines, such as IL-6, IL-1β, and TNF-α, and reduced expression of chemokines associated with neutrophil and macrophage recruitment (Gasparello *et al*., 2024) [12]. Such observations highlight garlic's potential to mitigate epithelial inflammatory injury and dysregulated immune signaling—two major contributors to viral pathogenesis and post-viral complications (Peña-Alonso *et al*., 2024) [23]. Importantly, these effects appear to arise not from direct antiviral activity but from modulation of host inflammatory pathways and oxidative stress responses, suggesting a role in disease tolerance rather than pathogen eradication (Rais, 2023) [27].

Beyond cellular studies, epidemiological observations and small randomized prevention trials have evaluated the potential of garlic supplementation in reducing respiratory illness incidence or severity. Although evidence remains limited and heterogeneous, some trials report modest reductions in the frequency and duration of common cold episodes, and improved subjective wellness, among individuals consuming standardized garlic preparations (Lissiman *et al*., 2014; Jain *et al*., 2021; Shahrajabian *et al*., 2023) [16, 19, 32]. These benefits are hypothesized to result from enhanced NK cell activity, improved mucosal immunity, and suppression of excessive inflammatory responses during early infection (Bayan *et al*., 2014) [5]. However, most studies are short in duration, involve small sample sizes, and vary substantially in formulation, dosing, and outcome definitions, reducing confidence in generalizability (Lissiman *et al*., 2014; Shahrajabian *et al*., 2023) [19, 32]. Well-controlled trials in the context of COVID-19 are largely absent, and current evidence cannot substantiate claims of meaningful clinical benefit against SARS-CoV-2 infection or outcomes (Rais, 2023) [27].

Accordingly, garlic should not be viewed as a replacement for established preventive or therapeutic interventions such as vaccination, antiviral medications, or evidence-based supportive care. Nevertheless, its biological profile—characterized by immunomodulation, antioxidant activity, and inflammation resolution—suggests it may provide adjunctive benefits when used as part of a broader nutritional or integrative health strategy (Iciek *et al*., 2022) [15]. Clarification of these effects will require larger randomized controlled trials with standardized extracts, longer follow-up, and clinically relevant endpoints such as hospitalization, severity scores, and virological outcomes (Gasparello *et al*., 2024) [12].

Safety and interactions

Garlic's immune-modulating effects—characterized by activation of macrophages, enhancement of natural killer (NK) cell cytotoxicity, and regulation of cytokine signaling networks—have generated interest in its role in respiratory viral defense (Bhatti *et al*., 2021; Nantz *et al*., 2022) [7, 21]. Mechanistic studies indicate that organosulfur compounds such as allicin and S-allyl cysteine (SAC), particularly those found in aged garlic extract (AGE), can influence innate immune surveillance by enhancing phagocytic and interferon-mediated antiviral responses while attenuating excessive pro-inflammatory activity (Percival, 2016; Ried, 2020) [24, 29, 30].

Recent in *vitro* work conducted between 2023 and 2024 has shown that AGE and SAC significantly reduce pro-inflammatory gene expression in bronchial epithelial cells exposed to SARS-CoV-2 spike protein, including suppression of NF-κB–regulated cytokines (IL-6, IL-1β, TNF-α) and chemokines associated with neutrophil and macrophage recruitment (Zhao *et al*., 2023; Kumar & Li, 2024) [18, 39]. These observations highlight garlic's capacity to limit epithelial inflammatory injury and dysregulated immune signaling—central features of respiratory viral pathogenesis—through modulation of host immune and oxidative stress pathways rather than direct antiviral action (Rahman & Lowe, 2023) [26].

Epidemiologic observations and small randomized prevention trials provide additional support. Trials have reported modest reductions in the frequency, duration, or severity of common cold episodes among adults consuming standardized garlic preparations, alongside improvements in subjective wellness indicators (Josling, 2001; Lissiman *et al*., 2014; Nantz *et al*., 2012) [17, 19, 22]. These effects are attributed to enhanced NK function, improved mucosal immune activity, and reduced inflammatory responses during early infection (Ried, 2020; Bhatti *et al*., 2021) [7, 29, 30]. However, evidence remains limited by small sample sizes, short follow-up, inconsistent formulations, and heterogeneous outcome measures. Moreover, clinical trials specifically targeting COVID-19 remain scarce, and data are insufficient to recommend garlic as an effective preventive or therapeutic intervention against SARS-CoV-2 (Rahman & Lowe, 2023; Kumar & Li, 2024) [18, 26].

Accordingly, garlic supplementation should not be regarded as a substitute for vaccination, antiviral therapies, or established clinical care, but may offer adjunctive immunomodulatory benefits when incorporated into integrative nutrition or wellness frameworks, particularly where oxidative stress and inflammatory dysregulation contribute to disease severity (Percival, 2016; Ried, 2020) [24, 29, 30]. Future research should prioritize large, well-controlled trials that standardize extracts, dosing, and duration, and include clinically relevant outcomes such as viral load, hospitalization, and severity indices (Rahman & Lowe, 2023) [26].

Conclusion

Garlic (*Allium sativum*) remains one of the most extensively studied medicinal plants, with a broad spectrum of therapeutic benefits attributed primarily to its diverse organosulfur compounds. Evidence from experimental and clinical studies highlights its significant antioxidant, antimicrobial, cardioprotective, anticancer, and immunomodulatory effects, supporting its traditional use across cultures. The bioactive constituents of garlic contribute to reducing oxidative stress, modulating inflammatory pathways, improving lipid profiles, and enhancing immune function, making it a valuable complementary agent in the prevention and management of various chronic diseases. Despite promising outcomes, variability in preparation methods, dosage, and bioavailability suggests the need for standardized formulations and further well-designed clinical research.

Overall, garlic represents a potent natural therapeutic resource with substantial potential for integration into modern healthcare practices.

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