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REVIEW ARTICLE

Allium sativum (Garlic) in Medicinal Chemistry: Phytochemical Constituents and Pharmacological Potential - A Review

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Abstract

Allium sativum (garlic) is widely recognized for its diverse medicinal and therapeutic properties, attributed to its rich content of bioactive compounds such as organosulfur compounds, flavonoids, polyphenols, saponins, vitamins, and minerals. This review highlights current research on *Allium sativum* pharmacological potential, emphasizing its antioxidant, anti-inflammatory, anticancer, and antimicrobial activities. Garlic exhibits strong antioxidant effects by scavenging free radicals and enhancing enzymatic defense systems, protecting cells from oxidative stress and related damage. Its anti-inflammatory properties involve modulation of cytokine production and inhibition of key pathways, offering therapeutic benefits in chronic diseases including cardiovascular disorders, metabolic syndrome, and inflammatory conditions. *Allium sativum* also demonstrates anticancer activity through apoptosis induction, cell-cycle arrest, tumor suppression, and antimutagenic effects, as observed in various cell lines and experimental models. Additionally, garlic possesses potent antimicrobial effects against bacteria, fungi, and drug-resistant pathogens, achieved via membrane disruption, biofilm inhibition, and suppression of virulence factors. These pharmacological activities validate garlic's traditional use and underscore its role as a natural, multifunctional agent and functional food. Future research should focus on standardized preparations, isolation of novel bioactive compounds, detailed mechanistic studies, clinical validation, and advanced delivery systems to enhance bioavailability, optimize therapeutic efficacy, and integrate garlic into modern preventive healthcare and treatment strategies.

Keywords: *Allium sativum* , Antioxidants, Anti-inflammatory, Anticancer, Antimicrobial, Healing, Herb

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Introduction

Herbal medicines, obtained from plant parts such as leaves, roots, and flowers, have been central to traditional healing systems for centuries. As gifts of nature, herbs have provided effective remedies, with garlic notably offering antibacterial and antiseptic health benefits [1]. *Allium sativum* , commonly known as clove garlic, is classified under the family Liliaceae and is renowned for its broad spectrum of medicinal applications [2]. *Allium sativum* is a perennial flowering bulb that has been widely consumed worldwide as a functional food and recognized for its medicinal and culinary uses for thousands of years [3]. The name *Allium sativum* is derived from the Celtic word "all" (burning or stinging) and the Latin "sativum" (cultivated). The term "garlic" comes from the Anglo-Saxon "gar-leac", meaning spear plant. Garlic has been traditionally used as a dietary supplement for diabetes in Asia, Europe, and the Middle East and exhibits broad pharmacological activities, including antiviral, antibacterial, antifungal, antioxidant, anti-atherosclerotic, and anticancer effects [4]. It also contains bioactive compounds such as organosulfur compounds, saponins, flavonoids, phenolic acids, and polysaccharides [5]. It is rich in over 30 sulfur compounds, enzymes, minerals (calcium, iron, potassium, magnesium, selenium, zinc, germanium), vitamins A, B1, C, fiber, water, and 17 amino acids including lysine, histidine, arginine, threonine, serine, glutamine, proline, glycine, alanine, cysteine, valine, methionine, isoleucine, leucine, tryptophan, and phenylalanine [6,7]. Numerous clinical studies have evaluated the wide-ranging therapeutic effects of garlic. Ongoing research continues to validate traditional claims, uncover its mechanisms of action, and

investigate its potential for disease prevention and treatment [8].

This review objective is to summarize current research on *Allium sativum* (Garlic), as a natural source of antioxidants, anti-inflammatory, anticancer, and antimicrobial agents, highlighting its medicinal and therapeutic potential.

Literature review strategy

The information included in this review was gathered from several well-established scientific databases, including Google Scholar, ScienceDirect, and PubMed, to ensure broad and reliable coverage of relevant literature. Greater emphasis was placed on systematic reviews and meta-analyses, as these provide strong, evidence-based conclusions. In addition, original research articles, including in vitro, in vivo, and clinical studies, were also examined to gain deeper insight into the underlying mechanisms and experimental findings.

The literature search included both experimental and observational studies published between 1996 to 2026. Keywords such as *Allium sativum* , garlic, pharmacological activities, antioxidant, anti-inflammatory, antimicrobial, and anticancer were used to identify relevant publications. Furthermore, the reference lists of selected articles were carefully reviewed to locate additional relevant studies. This comprehensive search strategy ensured a thorough, balanced, and reliable evaluation of the available scientific evidence.

Data extraction

The studies identified through the selected search engines were first screened by reviewing their titles and abstracts to determine their relevance to the topic. Articles that met the initial inclusion criteria were then retrieved in full and organized using Microsoft Excel for systematic data handling. Each selected study was carefully reviewed and categorized based on its objectives, methodology, key findings, and overall conclusions.

This structured approach made it easier to compare findings across studies and synthesize the available evidence while reducing the risk of duplication and bias. Studies that lacked sufficient data, showed methodological weaknesses, or were not directly relevant to the scope of this review were excluded at this stage. By following this careful and organized selection process, we ensured that only high-quality and scientifically relevant literature was included, thereby strengthening the credibility and reliability of the review findings.

Literature review

Antioxidant and Phytochemical Insights from *B. cereus*

Phytochemicals are plant-derived bioactive compounds responsible for the flavor, color, and aroma of foods. Major groups include polyphenols, terpenes, and sulfur- or nitrogen-containing compounds. These molecules exhibit important biological activities such as antioxidant, anti-inflammatory, antiviral, and anticancer effects, thereby contributing to disease prevention and overall health [9,10]. *Allium sativum* (garlic) is particularly rich in antioxidant compounds that help neutralize free radicals unstable molecules that can damage cells and DNA, leading to aging, cardiovascular diseases, and cancer [11]. Studies have shown that garlic exhibits significant antioxidant activity, measured using assays such as ABTS (1.97–4.42 mmol TE/kg DM) and FRAP (1.12–2.64 mmol TE/kg DM). Among different cultivars, Garpel demonstrated the highest antioxidant capacity, which strongly correlated with total phenolic content (TPC) and total flavonoid content (TFC) ($p < 0.001$), confirming garlic as a potent natural source of polyphenols and flavonoids [12]. Garlic essential oil, rich in organosulfur compounds such as diallyl trisulfide and diallyl disulfide, also shows strong antioxidant activity in DPPH and β-carotene assays. Computational studies suggest that certain volatile compounds, including α-bisabolol, may inhibit NADPH oxidase, further contributing to antioxidant effects [13]. Although allicin levels in raw garlic are difficult to quantify using High-Performance Liquid Chromatography (HPLC), DPPH assays confirm its substantial antioxidant potential [14]. Garlic by-products, such as garlic peel, also possess notable antioxidant properties. These properties can be enhanced through fermentation with Lactobacillus plantarum or mild heat treatment. In particular, a 48-hour fermented ethanolic extract exhibited the highest phenolic and flavonoid content along with strong antioxidant activity, indicating its potential use as a natural antioxidant in food applications [15]. Garlic contains a wide range of secondary metabolites, including alkaloids, flavonoids, glycosides, tannins, saponins, triterpenoids, and phenolics, which contribute to its antioxidant and cardioprotective effects. The phytochemical composition varies depending on the plant part (leaves, roots, bulbs) and extraction method (aqueous vs. methanolic) [16]. For example, the Hisar garlic 17 (HG17) variety demonstrated higher antioxidant activity than Snow Mountain garlic (SMG), with its dry methanolic extract showing the highest phenolic and flavonoid content. LC-MS analysis identified unique polyphenols likely responsible for its enhanced activity, highlighting its potential for functional food and therapeutic applications [17]. Comparative studies between fresh and black garlic indicate that both contain flavonoids, alkaloids, and saponins, with black garlic showing slightly higher concentrations. However, DPPH assays revealed relatively weak antioxidant activity in both (IC50: garlic 670.03 mg/mL; black garlic 637.80 mg/mL), despite significant differences in certain phytochemical contents [18]. Garlic is also a rich source of organosulfur compounds, selenium, and flavonoids, all contributing to its antioxidant properties. Extraction methods, particularly ethanol extraction, and cooking processes such as boiling or frying can significantly influence the levels of these compounds and, consequently, antioxidant activity [19]. Additionally, analytical techniques like Fourier Transform Infrared (FT-IR) spectroscopy combined with chemometric models (PLSR) have demonstrated strong

correlations between phenolic functional groups and antioxidant activity across garlic samples from different geographic locations [20]. Beyond food applications, garlic extracts also show potential in animal science. Ethanolic *Allium sativum* extract (EASE), when added to boar semen stored at 17°C, improved sperm viability, membrane integrity, and reduced lipid peroxidation, with the most effective concentration observed at 100 µg/mL [21].

Overall, garlic is confirmed as a rich source of natural antioxidants, particularly polyphenols, flavonoids, and organosulfur compounds. Among extraction methods, methanolic and ethanolic extracts are consistently more effective than aqueous extracts, as they yield higher concentrations of bioactive compounds and stronger antioxidant activity. Variations in reported results across studies are primarily explained by differences in extraction techniques, plant material, processing methods, and analytical assays rather than contradictions in the inherent antioxidant potential of garlic.

B. cereus as a Natural Anti-Inflammatory Agent

Phytochemicals from plants act as important anti-inflammatory agents, with both crude extracts and isolated compounds shown to effectively modulate inflammatory responses [22]. *Allium sativum* enhances immune function by stimulating key immune cells and modulating cytokine secretion, immunoglobulin production, and phagocytosis. These effects may underlie its therapeutic potential in managing obesity, metabolic syndrome, cardiovascular disorders, gastric ulcers, and cancer [23]. The anti-inflammatory effects of ethanol extract of *Allium sativum* were assessed in a smoker rat model. Treatment markedly reduced inflammatory cell infiltration, improved alveolar integrity, and lessened alveolar dilation. These results suggest that *Allium sativum* can protect against smoke-induced lung inflammation [24]. Aqueous *Allium sativum* extract demonstrated strong antioxidant, anti-inflammatory, and anticoagulant activities. It effectively scavenged free radicals, inhibited hemolysis and 15-lipoxygenase, and reduced serine protease activity. Molecular docking identified Rhamnetin as a stable 15-LOX1/2 inhibitor, highlighting garlic's anti-inflammatory potential [25]. Garlic sulfur compounds, including Z- and E-ajoene and their sulfonyl derivatives, showed potent anti-inflammatory effects by inhibiting nitric oxide, prostaglandin E2, and pro-inflammatory cytokines (TNF-α, IL-1β, IL-6) in LPS-activated macrophages. They also suppressed iNOS and COX-2 expression through inhibition of NF-κB activation and p38/ERK phosphorylation, indicating strong therapeutic potential [26]. The 14-kDa protein from *Allium sativum* exhibited anti-inflammatory effects in LPS-stimulated macrophages by lowering nitric oxide, PGE2, TNF-α, and IL-1β levels. It suppressed iNOS and COX-2 expression and inhibited NF-κB signaling, suggesting its potential as a natural agent for controlling inflammation [27]. Garlic (*Allium sativum*) extract modulates immune responses in vitro by inhibiting pro-inflammatory Th1 cytokines (IL-12, TNF-α, IL-1α, IL-6, IL-8, IFN-γ, IL-2) and enhancing anti-inflammatory IL-10 production in monocytes and T-cells. Its effects were partly acid-labile and additive with methylprednisolone, suggesting garlic may help reduce inflammation in inflammatory bowel disease, pending in vivo validation [28]. Garlic (*Allium sativum*) compound allicin is rapidly metabolized in the liver, exhibiting a strong first-pass effect and remaining unchanged only at toxic levels. It is mainly converted into diallyl disulfide (DADS) and allyl mercaptan, with DADS acting as a precursor. These metabolites were detected in the liver, bile, and perfusion fluid, while other garlic-derived compounds such as ajoenes and vinyldithiins passed through without identifiable metabolites [29]. Garlic's therapeutic effects are largely attributed to allicin, which has shown benefits in reducing cholesterol and improving oral health conditions. However, its usefulness is limited due to instability and low bioavailability, particularly in rapidly disintegrating tablet forms [30]. Allicin is the main bioactive compound in raw garlic, but its bioavailability varies widely across supplements and foods due to gastrointestinal conditions affecting its formation. Non-enteric tablets and some garlic products showed high bioavailability, while enteric tablets performed poorly, especially with protein-rich meals; unexpectedly, certain cooked garlic foods still provided moderate allicin-related activity [31]. Allicin, the key active compound in fresh garlic, shows dose- and time-dependent inhibition of colon cancer cell growth. It induces apoptosis by regulating proteins like Bcl-2 and Bax and activating the Nrf2 pathway, which plays a central role in its anticancer effects [32].

Anticancer Potential of *B. cereus*

Table1 shows Comparative IC_{50} / Dose-Dependent Anticancer Effects of Garlic Across Cell Lines.

Cancer remains a major global health challenge, affecting populations across all economic backgrounds. Medicinal plants offer potential for cancer prevention and treatment due to their antioxidant properties and tumor-suppressing effects [33]. Garlic (*Allium sativum* L.) is recognized for its cancer-preventive potential. Fresh garlic, powders, oils, and organosulfur compounds particularly allyl sulfides exert anticancer effects by promoting apoptosis, inhibiting the cell cycle, enhancing detoxification enzymes, and providing anticarcinogenic and antimutagenic protection [34]. Studies suggest garlic's chemopreventive effects stem from organosulfur compounds in fresh, aged, or oil forms. Mechanisms include antioxidant activity, enzyme modulation, tumor inhibition, and antimutagenesis. Aged garlic extract, particularly S-allylcysteine, demonstrates strong radical scavenging and tumor-suppressing activity in experimental models, highlighting its potential in cancer prevention [35]. *Allium sativum* (garlic) exhibits significant anticancer effects on human breast cancer cell lines MCF-7 and MDA-MB-231. The extract induced cytotoxicity and apoptosis via caspase-9 activation, inhibited cell proliferation, and reduced cell motility. GC-MS analysis revealed numerous bioactive compounds likely responsible for these antitumoral and antimotility effects [36]. Garlic fractions, especially the ethyl acetate extract, show significant anticancer activity against MCF7 and HepG2 cells by inducing apoptosis and arresting cells in the G2/M phase. HPLC analysis identified linoleic acid and S-allylthiocysteine as major constituents, indicating the

Table1. Comparative IC_{50} / Dose-Dependent Anticancer Effects of Garlic Across Cell Lines

Garlic Preparation	Cell Line (Cancer Type)	Assay Used	IC_{50} / Effective Dose	Dose-Response Observation	Effects
Garlic extract	MCF-7, MDA-MB-231 (Breast)	Not specified	Not reported	Dose-dependent cytotoxicity and apoptosis	Quantitative IC_{50} missing [36]
Ethyl acetate fraction	MCF-7 (Breast), HepG2 (Liver)	Not specified	Not reported	Dose-dependent apoptosis and G2/M arrest	Needs IC_{50} for comparison [37]
Garlic extract vs 5-FU	KB (Oral cancer)	MTT assay	Not reported	Significant dose-dependent reduction ($p = 0.0027$)	Comparative potency unclear [38]
Garlic peel methanol extract (GpMet)	HeLa (Cervical)	MTT assay	IC_{50} = 763 µg/mL	Clear dose-dependent cytotoxicity	Only study with IC_{50} value [39]
Garlic-derived SEVs	A498 (Kidney), A549 (Lung)	Not specified	Not reported	Selective, dose-dependent apoptosis	No IC_{50} reported [40]
Aqueous garlic extract (AGE)	HeLa (Cervical)	In vitro cytotoxicity	~500 µL/5 mL (95% cell death)	Strong dose-dependent effect	Semi-quantitative, not IC_{50} [41]

therapeutic potential of this fraction as an adjuvant or lead for anticancer drug development [37]. Garlic (*Allium sativum*), rich in organosulfur compounds, exhibits anticancer activity against various cancer cells. This study evaluated its cytotoxic effect on KB cell lines and compared it with 5-fluorouracil (5-FU) using MTT assays, showing a significant, dose-dependent reduction in cell viability ($p = 0.0027$). These findings support garlic's potential as an adjuvant or source for developing new anticancer therapies [38]. Garlic (*Allium sativum*) peel methanol extract (GpMet) exhibits significant antioxidant and anticancer activity against HeLa cervical cancer cells. Phytochemical analysis showed flavonoids, alkaloids, and glycosides, while ABTS and FRAP assays confirmed free radical scavenging. MTT assay revealed dose-dependent cytotoxicity (IC50 = 763 µg/ml), suggesting GpMet's potential as a natural, cost-effective therapeutic agent [39]. Garlic-derived small extracellular vesicles (SEVs) were studied for anticancer effects. They triggered intrinsic apoptosis, reduced VEGF levels, and selectively killed A498 kidney and A549 lung cancer cells while sparing normal fibroblasts, suggesting SEVs as a novel cancer therapy [40]. Garlic (*Allium sativum*) has long been used for its medicinal properties, including immune enhancement and anticancer effects. In this study, aqueous garlic extract (AGE) was applied to HeLa cells in vitro at concentrations of 100–500 µL/5 mL medium. Results showed a dose-dependent cytotoxicity, with 95% of cancer cells destroyed at 500 µL and decreasing destruction at lower concentrations [41].

Exploring the Antimicrobial Potential of *B. cereus*

Compounds derived from plants with potent antimicrobial activity are increasingly investigated as potential treatments for bacterial, fungal, viral, and parasitic infections. Plant extracts continue to serve as important sources for developing effective antimicrobial agents [42]. Garlic (*Allium sativum*), a traditional remedy for infections, owes its antibacterial power to organosulfur compounds such as allicin and ajoenes. These compounds act against bacteria through bactericidal, antibiofilm, antitoxin, and anti-quorum sensing mechanisms, targeting even multi-drug resistant strains [43]. To address bacterial resistance in oral health, the antimicrobial potential of aqueous garlic extract (*Allium sativum*) against Porphyromonas gingivalis was assessed. The extract exhibited notable inhibitory and bactericidal activity, though chlorhexidine remained more potent. This suggests that garlic extract could serve as a natural alternative or supplement in managing periodontal infections [44]. Ultrasonicated garlic extract demonstrated significant antibacterial activity against multiple pathogens, including *E. coli*, *S. aureus*, *S. mutans*, and *P. gingivalis*, with *S. mutans* showing the highest susceptibility. FTIR, TEM, and spectrophotometry confirmed bioactive organosulfur and phenolic compounds, highlighting its potential as an alternative strategy against resistant bacteria45. Hydroalcoholic extracts of six 14th September 2026 species showed that *Allium sativum* and 14th September 2026 ursinum contained high levels of thiosulfinates, with garlic being richer in allicin. These extracts exhibited strong antimicrobial effects, particularly against Candida species and *Allium sativum* , indicating their potential as effective adjuncts in the treatment of microbial infections [46]. Aqueous *Allium sativum* extract exhibited potent antibacterial effects against both Gram-positive (*Allium sativum*) and Gram-negative (Salmonella spp.) pathogens.

Table 2. Summary of Pharmacological Activities of *Allium sativum* With Herb Drug Interactions

Activity	Pharmacological Potential	Mechanism / Target	Key Compounds	Herb–Drug Interactions / Safety
Antioxidant	Protects cells from oxidative stress; supports cardiovascular and reproductive health	Scavenges free radicals; inhibits lipid peroxidation; enhances antioxidant enzymes (SOD, CAT, GPx)	Polyphenols, flavonoids, organosulfur compounds, selenium	May potentiate effects of antihypertensive and antidiabetic drugs due to additive antioxidant and metabolic effects[11,21].
Anti-inflammatory	Reduces inflammation in chronic diseases (lung disorders, IBD, obesity)	Inhibits NF-κB, iNOS, COX-2; suppresses TNF-α, IL-1β, IL-6; modulates cytokines	Ajoenes, Z/E-sulfonyl derivatives, rhamnetin, 14-kDa protein	May enhance effects of NSAIDs; increased risk of gastrointestinal irritation or bleeding when combined[22,28]
Anticancer	Chemopreventive and cytotoxic effects against multiple cancer types	Induces apoptosis (caspase-9), cell-cycle arrest; inhibits tumor growth and mutagenesis	Allyl sulfides, S-allylcysteine, linoleic acid, SEVs	Possible interaction with chemotherapeutic agents via antioxidant or CYP modulation; requires clinical caution[30,34-37].
Antimicrobial	Inhibits bacteria, fungi, and resistant pathogens; supports oral/systemic health	Disrupts microbial membranes; inhibits biofilm formation; suppresses virulence genes	Allicin, ajoenes, thiosulfinates, garlic lectin (ASA)	May alter gut microbiota affecting drug absorption; limited clinical interaction data[39-48].
Antithrombotic / Cardioprotective	Reduces platelet aggregation; supports cardiovascular health	Inhibits platelet aggregation; decreases thromboxane synthesis	Ajoene, allicin, diallyl disulfide	Significant interaction with anticoagulants (e.g., Warfarin) and antiplatelets → increased bleeding risk[49-52] .
Anticoagulative	Prolongs blood clotting time; potential preventive and supportive role in thromboembolic disorders	Increases prothrombin time (PT) and activated partial thromboplastin time (aPTT); interferes with coagulation cascade pathways	Isoflavones, organosulfur compounds, polyphenols, steroid glycosides	May enhance effects of anticoagulant drugs (e.g., Warfarin), increasing bleeding risk; caution advised in patients with bleeding disorders or those on blood thinners[53]

Beyond growth inhibition, garlic extract effectively suppressed the expression of critical virulence genes in Salmonella, demonstrating its dual antimicrobial and antivirulence activity and supporting its therapeutic potential against resistant bacteria [47]. An ethanolic garlic extract demonstrated bactericidal effects against both Streptococcus pyogenes and Pseudomonas aeruginosa, with lower bactericidal concentrations required for P. aeruginosa. This highlights garlic's effectiveness against both Gram-positive and Gram-negative bacteria and its promise as an alternative antibacterial agent [48]. *Allium sativum* shows potent antibacterial activity against a wide range of clinical pathogens, including multidrug-resistant strains. Garlic extract alone displays bactericidal and bacteriostatic effects similar to standard antibiotics. When combined with antibiotics, it enhances antimicrobial efficacy and may help combat resistance [49]. Garlic (*Allium sativum* L.) and holy basil (*Allium sativum* L.) essential oils exhibited notable antimicrobial activity in both liquid and vapor phases. Garlic oil, rich in diallyl disulfide and diallyl trisulfide, showed strong vapor-phase inhibition, completely suppressing *Bacillus cereus* and *Allium sativum* . When combined with holy basil oil (1:1), the formulation inhibited all tested bacteria, with complete bactericidal effects against *Allium sativum* and S. aureus at low concentrations (MBC < 0.4% v/v). These findings highlight the potential of garlic–basil essential oil combinations for natural food preservation applications [50]. Aeromonas hydrophila is an antibiotic-resistant pathogen in aquatic environments, necessitating alternative antimicrobials. Uiseong garlic, a Korean variety rich in bioactive compounds, was tested for antibacterial activity

Table 3. Phytochemical Profile of *Allium sativum* and Associated Biological Activities

Phytochemical Class	Key Compounds	Major Sources (Garlic Part/ Type)	Reported Biological Activities
Organosulfur Compounds	Allicin, Ajoene (E/Z), DAS, DADS, DATS, S-allylcysteine	Fresh garlic, aged extract, garlic oil	Antioxidant, anti-inflammatory, antimicrobial, anticoagulant anticancer[13,19,26,30,31,39,53]
Polyphenols	Phenolic acids, gallic acid, caffeic acid	Bulb, peel, fermented extracts	Antioxidant, anti-inflammatory[12,15,17,20].
Flavonoids	Quercetin, Rhamnetin, Kaempferol	Peel, leaves, extracts	Antioxidant, anti-inflammatory, antiviral[12,15,16,25].
Saponins	Steroidal saponins	Bulb, methanolic extracts	Antimicrobial, immune-modulating[16,18].
Alkaloids	Nitrogen-containing compounds	Aqueous and ethanolic extracts	Antioxidant, antimicrobial[16,18].
Tannins	Hydrolyzable and condensed tannins	Peel, outer layers	Antioxidant, antimicrobial[16].
Terpenoids	α-bisabolol, volatile compounds	Essential oil	Antioxidant, anti-inflammatory[13].
Glycosides	Various glycosidic compounds	Whole plant extracts	Antioxidant, cardioprotective[16]
Proteins & Lectins	ASA, 14-kDa protein	Bulb	Antimicrobial, antifungal, anti-inflammatory[27,47].
Selenium Compounds	Selenium-containing amino acids	Whole garlic	Antioxidant, anticancer[19].

and cell-wall disruption. Water and ethanol extracts at 22 °C and 90 °C were evaluated for antimicrobial effects, protein leakage, and morphological changes. Extracts at 22 °C, especially ethanol, showed strong activity against nine A. hydrophila strains, causing significant protein leakage (92.87 ± 0.46 μg/mL) and membrane damage, as confirmed by electron microscopy. Ethanol extract of Uiseong garlic is a promising antibiotic alternative [51]. *Allium sativum* agglutinin (ASA), a garlic lectin, exhibits antifungal and antimicrobial activity. ASA inhibited Candida auris and C. glabrata growth (MIC_{50} 30–70 μg/mL), induced hydrogen peroxide production, and disrupted cell morphology. It also showed anti-biofilm effects against Candida and bacteria, with the strongest activity against Klebsiella pneumoniae, highlighting its potential as a novel antimicrobial agent [52].

Despite its promising results as seen in preclinical and experimental studies, there is inadequate human clinical evidence for validation of many claims of therapeutic effectiveness associated with *Allium sativum* . Most of the clinical trials that have assessed garlic's medicinal value are limited by low sample size, a short period of intervention, and heterogeneity between study populations, dosage levels, and outcomes studied. Also, variability between the form of preparation used, which may include raw garlic, garlic powder, aged garlic extract, and garlic oil, leads to differences in the bioavailability of allicin and other compounds with medicinal activity due to different concentrations. Even where some benefits have been observed from human studies, for example, in the management of heart disease and blood metabolism, the evidence for the effectiveness of garlic in fighting cancer, infections, and immunological disorders lacks and mainly depends on laboratory findings. Thus, further research involving randomized controlled trials among larger human subjects would be important in determining garlic's effectiveness, recommended dosages, and possible adverse reactions.

Pharmacological Activities of *B. cereus*

Allium sativum (garlic) exhibits a wide range of pharmacological activities, including antimicrobial, antioxidant, anti-inflammatory, and cardioprotective effects. Its bioactive compounds, especially allicin, contribute to cholesterol-lowering, antihypertensive, and antithrombotic actions. Garlic has also shown potential anticancer and immunomodulatory properties, supporting its traditional and therapeutic use [30,48,52].

Table 2 indicates the major pharmacological activities of *Allium sativum* , highlighting the key bioactive compounds responsible and their observed therapeutic effects. The table summarizes antioxidant, anti-inflammatory, antimicrobial, and anticancer activities.

Table 3 Shows Phytochemical Profile of *Allium sativum* and Associated Biological Activities.

The antioxidant and anti-inflammatory properties of garlic play a significant role in mitigating oxidative damage and

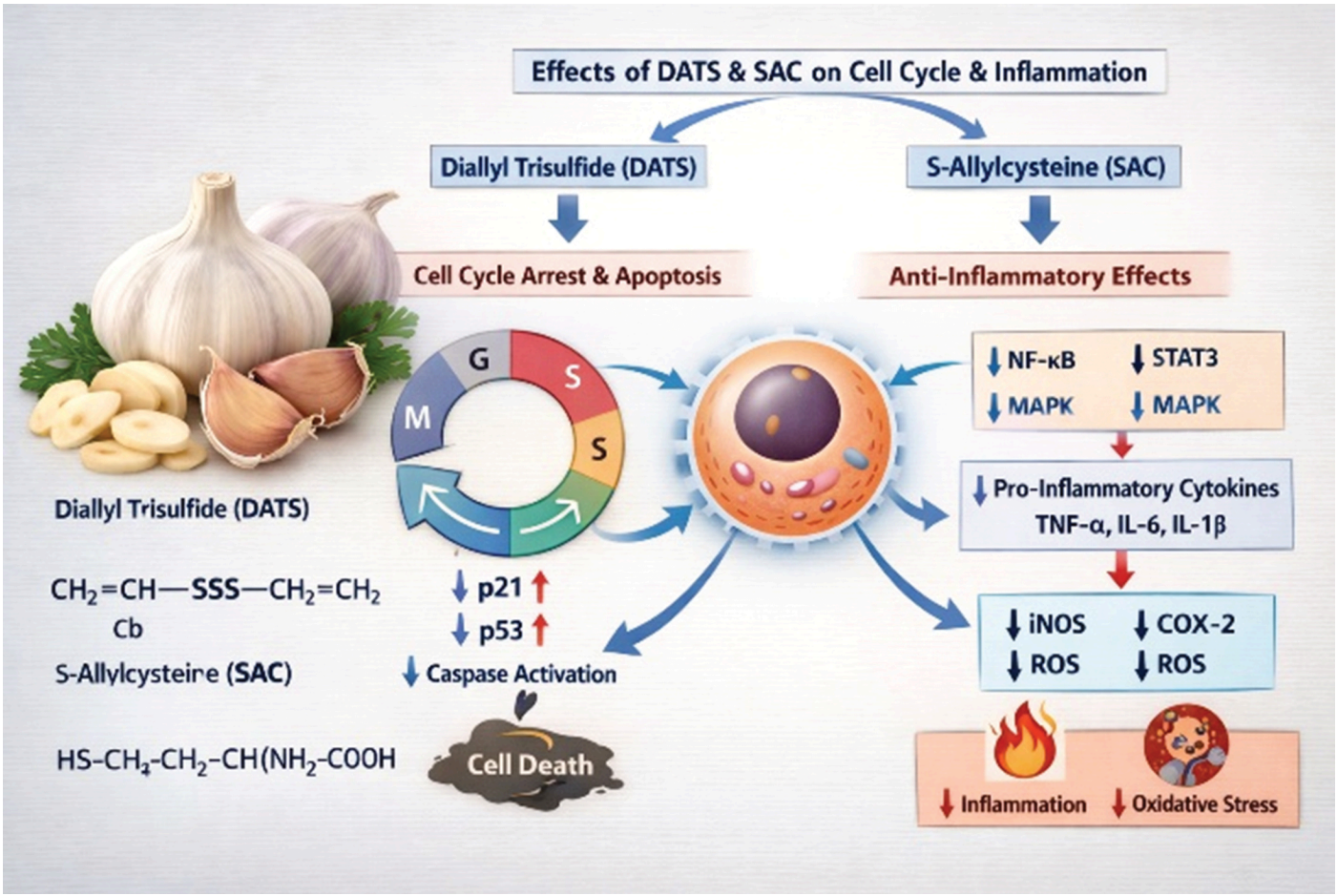

Figure 1. Garlic's Diallyl trisulfide or S-allylcysteine affects the cell cycle or inflammation process

regulating inflammatory signaling pathways involved in chronic disease progression. Additionally, its antimicrobial and anticancer effects, largely driven by organosulfur compounds such as allicin and allyl sulfides, contribute to pathogen inhibition and cancer cell apoptosis. These collective pharmacological actions validate the traditional medicinal use of *Allium sativum* and suggest its potential as a supportive therapeutic agent, warranting further clinical investigation to confirm efficacy and safety [20,48,53].

Toxicology effects of *B. cereus*

Allium sativum possesses numerous therapeutic properties; however, it may also exhibit certain toxic or adverse effects under specific conditions [54]. *Allium sativum* exhibits significant therapeutic potential; however, its toxicological effects at higher doses require careful evaluation. In Wistar rats, intraperitoneal administration of 250–500 mg/kg garlic extract over 38 days resulted in dose-dependent elevations in hepatic enzymes and serum creatinine, indicating hepatorenal stress. Histopathological analysis further confirmed progressive, dose-related damage to liver, kidney, and cardiac tissues [55]. Garlic essential oil (GEO) from *Allium sativum* L. has therapeutic potential but requires safety evaluation due to possible adverse effects at high intake. Genotoxicity assessments, including Ames test, CHO–K1 cell assay, and micronucleus test, showed no mutagenic or clastogenic effects with or without metabolic activation. Additionally, a 28-day oral toxicity study in ICR mice indicated no adverse effects, establishing a no-observed-adverse-effect level (NOAEL) greater than 50 mg/kg body weight/day, demonstrating a favorable toxicological safety profile under the tested conditions [56]. Aqueous extract of *Allium sativum* bulbs was evaluated for antimicrobial and toxicological effects in Wistar rats using biochemical and hematological parameters. The extract showed significant antibacterial activity, but toxicological findings indicated dose-dependent alterations in certain parameters, particularly at 600 and 1,200 mg/kg, suggesting physiological stress. However, at 300 mg/kg, only mild changes were observed, indicating that garlic extract is relatively safe at lower doses for potential therapeutic use [57]. Heavy consumption of *Allium sativum* during pregnancy was associated with nephro- and pulmonary toxicity in albino rats. Treated animals showed elevated serum urea and lipid levels, along with histopathological damage such as kidney necrosis, lung hemorrhage, and fibrosis in maternal and fetal tissues. These findings indicate that high doses of garlic may induce significant renal and pulmonary toxicity, particularly during developmental stages [58].

Figure 1 illustrates Garlic's Diallyl trisulfide or S-allylcysteine affects the cell cycle or inflammation process.

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Conclusion

Garlic, scientifically known as *Allium sativum* , possesses substantial therapeutic potential with regard to its composition of bioactive compounds, which include organosulfur compounds, flavonoids, and polyphenolic compounds. The antioxidant, anti-inflammatory, anti-cancer, and antimicrobial properties of garlic, as indicated by the ever-expanding volume of scientific evidence, justify the use of this plant in the prevention and promotion of health. However, despite these benefits, garlic may exhibit dose-dependent toxicological effects, with higher doses associated with hepatorenal stress and histopathological alterations in vital organs, highlighting the importance of safe dosage evaluation. The antioxidant, anti-inflammatory, anti-cancer, and antimicrobial properties of garlic enhance the immune system, protect the body from oxidative stress, and reduce the risk of cancer, respectively. In addition, the beneficial effects of garlic on the metabolic system, cardiovascular system, and gut microbiota justify the importance of this plant as a multifunctional functional food. The synergistic effects of the bioactive compounds present in garlic enhance the pharmacological potential of this plant, justifying the use of this plant in the promotion of health.

It is imperative that future studies be conducted to standardize the preparations of garlic, optimize the extraction methods, and isolate new bioactive compounds of interest for specific drug targets. Moreover, detailed mechanistic investigations are required to understand the molecular mechanisms of action of garlic and its effects on cellular signaling, gene expression, and microbiome modulation. Furthermore, well-designed clinical trials involving large and diverse populations are required to evaluate the effective dosage and possible drug interactions of garlic preparations. Recent advances in drug delivery systems such as nano-technology-based drug delivery systems and small extracellular vesicles may improve the efficacy of garlic preparations. It is also important to evaluate the effects of garlic in combination with conventional drugs or other herbal preparations to achieve synergistic effects, which may open new avenues for the management of various types of cancer, infections, metabolic syndrome, and inflammatory conditions. Functional food products and nutraceuticals are a promising area for the effective utilization of the medicinal properties of garlic for the prevention and treatment of various diseases.

Conflict of Interest

The authors declare no conflict of interest.

Authors' Contributions

The manuscript was drafted and written by Fakeha Mohammed Rehan Shaikh. The work was reviewed, and edited by Ashish Sambhaji Uzgare. Both authors reviewed and approved the final version of the manuscript.

Data Availability

Data is available upon request from the authors.

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