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Allium sativum L.: A comprehensive review of its phytochemistry, pharmacological properties and therapeutic potential

M. Karal Marks, C. Ravindran*◆, K. Nageshwari, M. Gnanasekaran, K. Kalpana***, M. Kabilan**** and M. Vignesh**

Department of Vegetable Science, Horticultural College and Research Institute, Tamil Nadu Agricultural University, Periyakulam-625604, Theni, Tamil Nadu, India

* *Department of Horticulture, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai-625104, Tamil Nadu, India*

** *Department of Plant Breeding and Genetics, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai-625104, Tamil Nadu, India*

*** *Department of Plant Protection, Horticultural College and Research Institute, Tamil Nadu Agricultural University, Periyakulam-625604, Theni, Tamil Nadu, India*

**** *Division of Soil Science and Agricultural Chemistry, Regional Coffee Research Station, Coffee Board, Thandigudi-624216, Dindigul, Tamil Nadu, India*

***** *Department of Vegetable Science, Horticultural College and Research Institute, Tamil Nadu Agricultural University, coimbatore-641003, Tamil Nadu, India*

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Abstract

Allium sativum L. is one of the oldest cultivated medicinal plants, widely recognized for its nutritional, therapeutic and pharmacological significance. This review provides a comprehensive overview of the phytochemistry, biological activities and therapeutic potential of garlic, integrating traditional knowledge with recent scientific advancements. Garlic is rich in bioactive constituents, particularly organosulfur compounds such as allicin, alliin, diallyl sulfides and S-allyl cysteine, along with phenolics, flavonoids, saponins and polysaccharides. These compounds collectively contribute to its diverse pharmacological properties. Extensive experimental and clinical studies demonstrate that garlic exhibits strong antioxidant activity by scavenging free radicals and enhancing endogenous antioxidant defense systems. It also shows broad-spectrum antimicrobial effects against bacteria, fungi and viruses, along with significant anti-inflammatory activity through the modulation of cytokines and inhibition of key signaling pathways such as NF-κB. Furthermore, garlic plays a vital role in the prevention and management of chronic diseases, including cardiovascular disorders, diabetes and cancer, through mechanisms such as lipid regulation, blood pressure control, apoptosis induction and improvement of insulin sensitivity. Recent advances in nanotechnology, omics approaches and formulation strategies have enhanced the bioavailability and therapeutic efficacy of garlic-derived compounds. The development of value-added products such as aged garlic extract, garlic oil and standardized supplements has expanded its applications in the nutraceutical and pharmaceutical industries. Additionally, garlic is increasingly incorporated into functional foods and cosmeceutical products, reflecting its multifunctional utility. Despite its promising potential, several challenges remain, including variability in phytochemical composition, instability of key bioactive compounds and the lack of standardized clinical trials. Addressing these limitations through advanced research, genetic improvement and standardized formulations is essential for optimizing its therapeutic use. In conclusion, garlic represents a potent natural resource with significant health benefits and continued interdisciplinary research will facilitate its integration into modern healthcare systems and evidence-based medicine.

1. Introduction

Allium sativum L. is one of the oldest cultivated plant species and continues to hold immense importance in both culinary and medicinal domains. Belonging to the family Amaryllidaceae, garlic has been utilized for thousands of years across diverse civilizations, including those of ancient Egypt, China, India and Greece. Historical evidence suggests that garlic was valued not only as a food ingredient but also as a therapeutic agent used to treat infections, digestive ailments, respiratory disorders and cardiovascular conditions. Its long-standing presence in traditional systems such as Ayurveda and Traditional Chinese Medicine reflects its perceived efficacy as a natural remedy for enhancing vitality and promoting overall health. Even today, garlic remains a staple in global diets, bridging the gap between traditional knowledge and modern scientific validation (Bachrach, 2025). In recent years, there has been a growing resurgence of interest in plant-based therapeutics due to increasing concerns regarding the adverse effects of synthetic drugs and the global burden of chronic diseases. Garlic has emerged as a prominent candidate in this context,

Corresponding author: Dr. C. Ravindran
Associate Professor (Horticulture), Department of Horticulture, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai-625104, Tamil Nadu, India
E-mail: ravindran.c@tnau.ac.in
Tel.: +91-9380823451

owing to its diverse bioactive constituents and broad-spectrum pharmacological activities. The concept of functional foods, which emphasizes the role of diet in disease prevention and health promotion, has further elevated the importance of garlic. Unlike many medicinal plants that require specialized preparation, garlic is widely consumed as part of daily meals, making it an accessible and cost-effective option for improving public health outcomes. Contemporary research trends indicate a steady increase in scientific publications related to garlic, reflecting its expanding relevance in biomedical and nutritional sciences (Rana *et al*., 2024). The therapeutic potential of garlic is primarily attributed to its rich phytochemical composition, particularly organosulfur compounds. Among these, allicin is recognized as the principal bioactive molecule responsible for many of garlic's medicinal properties. Notably, allicin is not present in intact garlic cloves but is formed enzymatically when garlic is crushed or chopped, facilitating the conversion of alliin by the enzyme alliinase. This transformation produces a highly reactive compound that contributes to garlic's characteristic odor and biological activity (Chen *et al*., 2025). In addition to allicin, garlic contains several other sulfur-containing compounds such as diallyl disulfide, diallyl trisulfide, ajoene and S-allyl cysteine, each exhibiting distinct pharmacological effects. These compounds, along with phenolics, flavonoids and saponins, collectively contribute to the antioxidant, antimicrobial and anti-inflammatory properties of garlic (Tudu *et al*., 2022; El-Saadony *et al*., 2024). The pharmacological activities of garlic have been extensively investigated in both *in vitro* and *in vivo* studies, providing scientific support for its traditional uses. One of the most significant properties of garlic is its antioxidant capacity, which plays a crucial role in neutralizing reactive oxygen species and reducing oxidative stress. Oxidative stress is a major contributing factor in the pathogenesis of various chronic diseases, including cardiovascular disorders, cancer, diabetes and neurodegenerative conditions. Garlic-derived compounds enhance endogenous antioxidant defense systems, thereby protecting cellular components from oxidative damage (Iqbal *et al*., 2025). This antioxidant potential is closely linked to the presence of phenolic compounds and sulfur-containing molecules, which act synergistically to improve cellular resilience.

In addition to its antioxidant activity, garlic exhibits potent antimicrobial properties against a wide range of pathogens, including bacteria, fungi, viruses and parasites. The antimicrobial efficacy of garlic is largely attributed to its organosulfur compounds, which can disrupt microbial cell membranes, inhibit enzyme activity and interfere with nucleic acid synthesis. These properties have positioned garlic as a promising alternative to conventional antimicrobial agents, particularly in the context of rising antibiotic resistance. Recent studies have highlighted its potential use in food preservation and pharmaceutical applications, further emphasizing its relevance in addressing global health challenges (Cupertino *et al*., 2024). Garlic also demonstrates significant anti-inflammatory effects by modulating key signaling pathways and reducing the production of pro-inflammatory cytokines. Chronic inflammation is increasingly recognized as a central factor in the development of numerous non-communicable diseases, including cardiovascular disease, diabetes and cancer. By suppressing inflammatory mediators and enhancing anti-inflammatory responses, garlic contributes to the maintenance of physiological homeostasis. These anti-inflammatory properties are closely associated with its bioactive constituents, which interact with molecular targets involved in inflammation and immune regulation (El-Saadony *et al*., 2024). Among the various therapeutic applications of garlic, its role in cardiovascular health has been the subject of extensive research. Studies have demonstrated that garlic can reduce serum cholesterol levels, lower blood pressure, inhibit platelet aggregation and improve endothelial function. These effects collectively contribute to its cardioprotective properties and its potential to prevent atherosclerosis and related cardiovascular disorders. Mechanistically, garlic compounds are known to inhibit key enzymes involved in cholesterol biosynthesis, enhance nitric oxide production and modulate vascular tone. Furthermore, its antiplatelet activity reduces the risk of thrombosis, thereby improving overall cardiovascular health (Azam *et al*., 2025). Clinical evidence also supports the efficacy of garlic supplementation in reducing blood pressure, particularly in hypertensive individuals (Tang *et al*., 2025).

Garlic has also gained attention for its potential anticancer properties, with studies indicating that its bioactive compounds can inhibit tumor growth, induce apoptosis and modulate carcinogen metabolism. These effects are mediated through multiple pathways, including the regulation of cell cycle progression, enhancement of detoxification enzymes and reduction of oxidative DNA damage. Although, further clinical validation is required, existing evidence suggests that regular consumption of garlic may reduce the risk of certain cancers, particularly those affecting the gastrointestinal tract (Rajpoot *et al*., 2026). In the context of metabolic disorders, garlic has shown promising antidiabetic effects. It has been reported to improve insulin sensitivity, regulate blood glucose levels and reduce oxidative stress and inflammation associated with diabetes. Preclinical and clinical studies suggest that garlic-derived compounds, particularly allicin, play a key role in enhancing metabolic control and reducing complications related to diabetes (Singh *et al*., 2025). Additionally, computational studies have indicated that garlic compounds such as alliin may interact with key enzymes involved in glucose metabolism, further supporting its antidiabetic potential (Salam, 2025). Neuroprotective effects of garlic are another emerging area of research, with studies suggesting that its antioxidant and anti-inflammatory properties may help prevent neurodegenerative diseases such as Alzheimer's and Parkinson's disease. By reducing oxidative stress and modulating neurotransmitter systems, garlic may contribute to improved cognitive function and neuronal health. Similarly, garlic has demonstrated hepatoprotective and renoprotective effects, highlighting its role in maintaining organ health and preventing toxicity-induced damage (Kumar *et al*., 2026).

Despite the extensive pharmacological potential of garlic, several challenges must be addressed to fully harness its benefits. One of the primary limitations is the variability in the composition and concentration of bioactive compounds, which can be influenced by factors such as cultivar, environmental conditions and processing methods. The instability of allicin, in particular, poses a significant challenge for standardization and formulation. Processing techniques such as aging have been shown to improve the stability and bioavailability of certain compounds, such as S-allyl cysteine, which exhibits enhanced therapeutic efficacy and reduced toxicity (Amer *et al*., 2025). Another important consideration is the bioavailability of garlic-derived compounds, which can vary depending on the form in which garlic is consumed. Raw garlic, garlic powder, garlic oil and aged garlic extract each differ in their chemical composition and biological activity. Advances in pharmaceutical technologies, including nanoencapsulation and targeted delivery systems, are being explored to improve the stability and efficacy of garlic bioactives. These approaches aim to overcome the limitations associated with rapid degradation and poor absorption of certain compounds, thereby enhancing their therapeutic potential (El-Saadony *et al*., 2024). From an agricultural perspective, garlic is an economically significant crop cultivated across various agro-climatic regions. Major producers include China, India and Mediterranean countries, where garlic contributes substantially to agricultural income and trade. Advances in agronomic practices, including improved irrigation, nutrient management and pest control strategies, have enhanced garlic productivity and quality. Additionally, the development of value-added products such as garlic powder, garlic oil and aged garlic extract has expanded its industrial applications and market potential (Wiley *et al*., 2025). Garlic also plays a role in sustainable agriculture and food systems. Its antimicrobial and pesticidal properties make it a potential natural alternative to chemical inputs in farming. Furthermore, garlic by-products are being explored for their bioactive potential, contributing to waste valorization and circular economy approaches. These applications align with global efforts to promote environmentally sustainable practices and reduce the ecological footprint of agriculture.

A. sativum represents a multifaceted plant with significant potential in the fields of nutrition, medicine and agriculture. Its rich phytochemical composition and diverse pharmacological activities make it a valuable resource for addressing contemporary health challenges. However, further research is needed to standardize its formulations, optimize its bioavailability and validate its clinical efficacy. This review aims to provide a comprehensive overview of the phytochemistry, pharmacological properties and therapeutic potential of garlic, integrating traditional knowledge with modern scientific advancements to highlight its role as a functional food and natural therapeutic agent.

2. Botanical description and taxonomy of garlic

A. sativum, commonly known as garlic, is a monocotyledonous, bulb-forming perennial herb belonging to the genus *Allium*, which includes other economically important crops such as onion, leek and shallot. With advancements in molecular phylogenetics, garlic is now classified under the family Amaryllidaceae (subfamily Allioideae), replacing its earlier placement in Liliaceae (Li *et al*., 2021; Sharma and Rao, 2023). The complete taxonomic hierarchy includes Kingdom Plantae, Division Magnoliophyta (angiosperms), Class Liliopsida (monocots), Order Asparagales, Family Amaryllidaceae, Genus *Allium* and Species *A. sativum*. Garlic is a diploid species (2n = 16) and is widely believed to have originated from its wild progenitor *Allium longicuspis*, although its domestication history remains under investigation (Kamenetsky *et al*., 2022; Singh *et al*., 2024). Due to sterility and poor seed production in most cultivated forms, garlic is propagated vegetatively through cloves, which limits genetic recombination and contributes to relatively narrow genetic diversity (Volk *et al*., 2020; Tripathy *et al*., 2025). Morphologically, garlic is distinguished by its underground bulb, which is the principal economic organ. The bulb is composed of multiple cloves arranged concentrically around a basal plate, each enclosed in a papery tunic that provides protection against environmental stress and pathogens (Brewster, 2020; Tudu *et al*., 2022). The number of cloves per bulb varies depending on the cultivar, typically ranging from 6 to 20 and each clove represents a modified bud capable of developing into a new plant. The basal plate produces adventitious roots, while the aerial portion forms a pseudo-stem made up of tightly overlapping leaf sheaths. The leaves are linear, flat and bluish-green, usually measuring 30-60 cm in length and are arranged alternately along the pseudo-stem. These leaves are photosynthetically active and play a crucial role in assimilate production and translocation to the developing bulb (Ricroch *et al*., 2020; Yadav *et al*., 2023).

The reproductive biology of garlic is unique due to its limited ability to produce viable seeds. In certain genotypes, particularly hardneck types, a flowering stalk known as a scape emerges from the center of the plant. This scape terminates in an umbel-type inflorescence enclosed by a membranous spathe. However, instead of producing fertile seeds, most cultivated garlic varieties form bulbils small aerial propagules that can be used for multiplication, although they require longer growth cycles to produce mature bulbs (Kamenetsky and Rabinowitch, 2021; Tripathy *et al*., 2025). The sterility of garlic is attributed to long-term vegetative propagation and genetic degeneration, which has reduced its reproductive capacity over time. Based on morphological and physiological traits, garlic is broadly classified into two main groups: hardneck (bolting) and softneck (non-bolting) types. Hardneck garlic (*A. sativum* var. *ophioscorodon*) produces a central flowering stalk and typically has fewer but larger cloves arranged in a single whorl. These types are well adapted to cooler climates and are known for their strong flavor and higher culinary quality (Volk *et al*., 2020; Singh *et al*., 2024). In contrast, softneck garlic (*A. sativum* var. *sativum)* lacks a scape and contains a larger number of smaller cloves arranged in multiple layers. Softneck varieties are widely cultivated due to their superior storage ability, higher yield potential and adaptability to diverse environmental conditions (Sharma and Rao, 2023). In India, several improved cultivars have been developed through breeding programs, including Yamuna Safed (G-1), Yamuna Safed-2 (G-50), Agrifound White (G-41) and Ooty-1, which are known for their high yield, uniform bulb size and resistance to pests and diseases (ICAR, 2022; Yadav *et al*., 2023).

Garlic is cultivated extensively across temperate, subtropical and tropical regions, making it one of the most widely distributed spice crops globally. It grows best in well-drained loamy soils with moderate fertility and requires a cool climate during vegetative growth followed by warmer conditions for bulb development. Environmental factors such as temperature, photoperiod and soil moisture significantly influence bulb initiation, clove differentiation and overall yield (Brewster, 2020; Singh *et al*., 2024). China is the largest producer of garlic worldwide, followed by India, which is a major contributor to global production and export. Other significant producers include Bangladesh, Egypt, South Korea, Spain and the United States (Faostat, 2024; Tripathy *et al*., 2025). In India, garlic is primarily cultivated as a rabi crop in states such as Madhya Pradesh, Gujarat, Rajasthan, Uttar Pradesh and Tamil Nadu, with planting typically occurring in October-November and harvesting in March-April (ICAR, 2022; Yadav *et al*., 2023). Its adaptability to diverse agro-climatic conditions, coupled with high market demand and relatively low input requirements, makes garlic an economically important crop for both smallholder and commercial farming systems. Furthermore, its extensive use in culinary, medicinal and industrial applications reinforces its global significance as a multifunctional crop species.

3. Nutritional composition of garlic

Garlic is widely recognized as a nutrient-dense functional food, providing a combination of macronutrients, micronutrients and biologically active compounds that contribute to its health-promoting properties. Although, consumed in relatively small quantities, garlic offers a concentrated source of essential nutrients. Among macronutrients, carbohydrates constitute the major fraction, typically present in the form of fructans such as inulin-type polysaccharides, which function as storage carbohydrates and exhibit prebiotic properties that support gut microbiota and digestive health (Figure 1). In addition to carbohydrates, garlic contains moderate amounts of proteins, including essential amino acids and small quantities of lipids. The dietary fiber content, although modest, plays a role in regulating digestion, improving bowel function and contributing to metabolic health. Studies indicate that garlic contains a complex matrix of carbohydrates, amino acids and dietary fibers that collectively contribute to its nutritional and functional significance (Adamoviæ *et al*., 2026; Gupta *et al*., 2024). In terms of micronutrients, garlic is a valuable source of several vitamins and minerals essential for physiological processes. It is particularly rich in vitamin C (ascorbic acid), which plays a crucial role in antioxidant defense, immune function and collagen synthesis. Vitamin B6 (pyridoxine), another important component, is involved in amino acid metabolism, neurotransmitter synthesis and cardiovascular regulation through homocysteine metabolism. Garlic also contains smaller amounts of other B-complex vitamins such as thiamine and riboflavin, which contribute to energy metabolism. Mineral composition is another notable aspect of garlic nutrition, with significant levels of selenium, calcium, phosphorus, potassium, magnesium and trace elements. Selenium is especially important due to its role in the activity of antioxidant enzymes such as glutathione peroxidase, thereby protecting cells from oxidative damage. Calcium and phosphorus contribute to bone health, while potassium helps maintain electrolyte balance and regulate blood pressure. These micronutrients, in combination with sulfur-containing compounds, enhance the overall nutritional and therapeutic value of garlic (Fernandez *et al*., 2025; Gupta *et al*., 2024).

When compared with other members of the genus *Allium*, such as onion (*A. cepa*), garlic exhibits a more concentrated nutritional profile due to its lower moisture content and higher dry matter accumulation. Comparative studies have shown that garlic generally contains higher levels of carbohydrates, fiber and certain minerals, whereas onion tends to have higher moisture and slightly higher protein content. For instance, garlic has been reported to possess greater amounts of carbohydrates and ash content compared to onion, while onion exhibits higher moisture and protein levels, highlighting species-specific nutritional variation (Salawu *et al*., 2021; comparative analyses, 2023). Furthermore, garlic contains a higher concentration of organosulfur compounds, which significantly enhance its antioxidant, antimicrobial and cardioprotective properties relative to other *Allium* crops. However, onions and related species may contain higher levels of certain flavonoids such as quercetin, indicating that each *Allium* species offers unique nutritional and phytochemical benefits (Bedir *et al*., 2025).

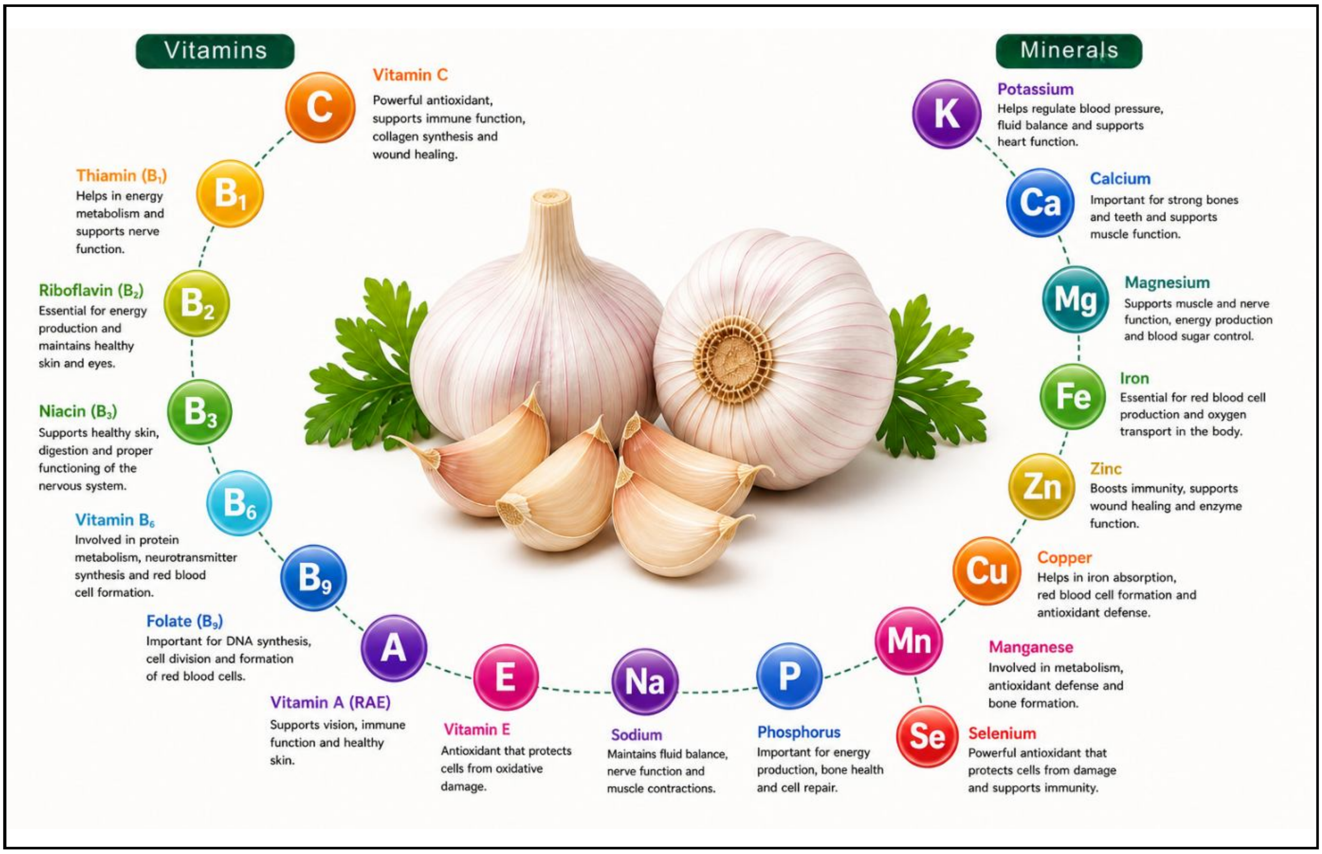

Figure 1: Nutritional composition of garlic (Source: Prepared by us with the help of Biorender software).

Overall, the nutritional composition of garlic underscores its importance as a compact yet potent source of essential nutrients and bioactive compounds. Its combination of macronutrients, micronutrients and functional phytochemicals contributes to its classification as a nutraceutical food with significant health benefits. The synergistic interaction between these components enhances its biological efficacy, making garlic not only a culinary ingredient but also a valuable component in preventive nutrition and therapeutic applications.

Table 1: Major bioactive compounds of *A. sativum* and their functions

Compound class	Key compounds	Chemical nature	Biological functions	References
Organosulfur compounds	Allicin, alliin, ajoene, diallyl sulfide	Sulfur-containing volatile compounds	Antimicrobial, anticancer, antioxidant, cardioprotective	Borlinghaus *et al.*, 2021; Batiha *et al.*, 2020
Polyphenols	Flavonoids, phenolic acids	Secondary metabolites	Antioxidant, anti-inflammatory	Shang *et al.*, 2023; Liu *et al.*, 2021
Saponins	Steroidal saponins	Glycosidic compounds	Anticancer, cholesterol-lowering	Okoro *et al.*, 2023
Polysaccharides	Fructans, inulin-type compounds	Carbohydrate polymers	Immunomodulatory, prebiotic effects	Liu *et al.*, 2021
Vitamins and minerals	Vitamin C, B6, selenium	Micronutrients	Immune support, metabolic regulation	Amagase, 2020

4. Phytochemistry of garlic

The phytochemical composition of *A. sativum* is highly complex and accounts for its diverse biological and therapeutic properties. Garlic contains a wide spectrum of primary and secondary metabolites, among which organosulfur compounds are the most characteristic and biologically active constituents. In addition, it is rich in phenolics, flavonoids, saponins and polysaccharides that collectively contribute to its antioxidant, antimicrobial and pharmacological potential (Table 1). The composition and concentration of these compounds vary depending on genotype, environmental conditions and processing methods, making garlic a chemically dynamic plant system (El-Saadony *et al*., 2024; Tudu *et al*., 2022).

4.1 Major bioactive compounds

The most distinctive phytochemicals in garlic are organosulfur compounds, which are responsible for its pungent aroma and most of its biological activities. The primary sulfur-containing precursor is alliin (S-allyl-L-cysteine sulfoxide), which is converted enzymatically into allicin upon tissue disruption. Allicin is highly reactive and unstable, rapidly transforming into a variety of lipid-soluble sulfur compounds such as diallyl disulfide (DADS), diallyl trisulfide (DATS) and ajoene. These compounds exhibit strong antimicrobial, antioxidant, anti-inflammatory and anticancer properties by interacting with thiol groups of proteins and modulating cellular redox status (Borlinghaus *et al*., 2021; Chen *et al*., 2025). In addition to volatile sulfur compounds, garlic also contains water-soluble derivatives such as S-allyl cysteine (SAC) and S-allyl mercaptocysteine (SAMC), particularly abundant in aged garlic extracts, which are more stable and bioavailable. Apart from sulfur compounds, garlic contains significant amounts of phenolic compounds and flavonoids, including quercetin, kaempferol and phenolic acids such as caffeic and ferulic acids. These compounds contribute to garlic's antioxidant capacity by scavenging free radicals, chelating metal ions and modulating antioxidant enzyme systems. Although, the concentration of flavonoids in garlic is generally lower than in some other vegetables, their synergistic interaction with sulfur compounds enhances the overall biological activity (Shang *et al*., 2023; El-Saadony *et al*., 2024).

Garlic also contains saponins and polysaccharides, which play important roles in its pharmacological effects. Steroidal saponins present in garlic have been associated with cholesterol-lowering, anticancer and immunomodulatory activities. Meanwhile, garlic polysaccharides, particularly fructans such as inulin, exhibit prebiotic effects by promoting beneficial gut microbiota. These polysaccharides also contribute to antioxidant and immunostimulatory activities, further expanding the therapeutic potential of garlic (Liu *et al*., 2021; Kumar *et al*., 2024).

4.2 Formation and stability of bioactive compounds

The formation of garlic's key bioactive compounds is closely linked to enzymatic processes that occur upon tissue damage. In intact garlic cloves, alliin is stored separately from the enzyme alliinase within different cellular compartments. When garlic is crushed, chopped, or chewed, cellular disruption allows alliinase to catalyze the conversion of alliin into allicin, which is responsible for the characteristic odor and many of the biological activities of fresh garlic. This reaction occurs rapidly and is highly dependent on environmental factors such as pH and temperature (Borlinghaus *et al*., 2021; Chen *et al*., 2025).

However, allicin is chemically unstable and undergoes rapid decomposition into secondary sulfur compounds such as diallyl sulfides and ajoene. The stability of these compounds is significantly influenced by processing methods. For instance, crushing garlic and allowing it to stand for a few minutes before cooking enhances allicin formation, whereas immediate heating can inactivate alliinase and reduce allicin yield. Thermal processing, such as boiling or frying, leads to the degradation of volatile sulfur compounds but may increase the concentration of more stable compounds. Similarly, aging processes, as used in the preparation of aged garlic extract, convert unstable sulfur compounds into stable, water-soluble derivatives like S-allyl cysteine, which exhibit improved bioavailability and reduced toxicity (Amagase, 2020; El-Saadony *et al*., 2024).

4.3 Chemical properties

The biological activity of garlic compounds is strongly influenced by their chemical properties, particularly the presence of sulfur atoms and functional groups capable of redox reactions. Structure–

activity relationship (SAR) studies have shown that the number of sulfur atoms and the type of chemical bonds significantly affect the reactivity and pharmacological properties of these compounds. For example, diallyl trisulfide (DATS), which contains three sulfur atoms, generally exhibits stronger biological activity than diallyl disulfide (DADS) due to its higher reactivity with cellular thiols. Similarly, the electrophilic nature of allicin allows it to interact with cysteine residues in proteins, thereby modulating enzyme activity and signaling pathways (Iciek *et al*., 2022; Shang *et al*., 2023).

Garlic phytochemicals can be broadly classified into volatile and non-volatile compounds based on their chemical properties. Volatile compounds, including allicin, diallyl sulfides and ajoene, are responsible for garlic's aroma and are typically lipid-soluble. These compounds are highly reactive and contribute to antimicrobial and anticancer activities but are relatively unstable. In contrast, non-volatile compounds such as S-allyl cysteine, S-allyl mercaptocysteine and polysaccharides are water-soluble, more stable and exhibit longer-lasting biological effects, particularly in antioxidant and cardioprotective functions. The balance between volatile and non-volatile compounds is influenced by processing methods and determines the overall efficacy of garlic-based preparations (Liu *et al*., 2021; Kumar *et al*., 2024).

5. Pharmacological properties of garlic

Garlic exhibits a broad spectrum of pharmacological activities that have been validated through extensive *in vitro, in vivo* and clinical studies. These biological effects are primarily attributed to its rich pool of organosulfur compounds, phenolics and other secondary metabolites, which act through multiple molecular targets and signaling pathways (Table 2 and Figure 2). Among the most prominent pharmacological properties of garlic are its antioxidant, antimicrobial and anti-inflammatory activities, which collectively contribute to its role in preventing and managing various chronic and infectious diseases (El-Saadony *et al*., 2024; Shang *et al*., 2023).

Table 2: Pharmacological activities of garlic and mechanisms of action

Biological activity	Mechanism of action	Target system	Key outcomes	References
Antioxidant	Scavenging ROS, enhancing antioxidant enzymes	Cellular metabolism	Reduced oxidative stress	Ansary *et al*., 2020; Shang *et al*., 2023
Antimicrobial	Disruption of microbial cell membranes	Bacteria, fungi	Growth inhibition	Borlinghaus *et al*., 2021
Cardioprotective	Vasodilation, inhibition of cholesterol synthesis	Cardiovascular system	Reduced BP, improved lipid profile	Ried *et al*., 2020
Anticancer	Induction of apoptosis, inhibition of tumor growth	Cancer cells	Reduced proliferation	El-Saadony *et al*., 2024
Antidiabetic	Regulation of glucose metabolism enzymes	Endocrine system	Improved insulin sensitivity	Singh *et al*., 2025
Immunomodulatory	Activation of immune cells, cytokine modulation	Immune system	Enhanced immunity	El-Tahan *et al*., 2024

5.1 Antioxidant activity

The antioxidant activity of garlic is one of its most well-documented pharmacological properties and plays a crucial role in protecting biological systems from oxidative stress. Garlic-derived compounds such as allicin, S-allyl cysteine and various phenolics act as potent free radical scavengers, neutralizing reactive oxygen species (ROS) and reactive nitrogen species (RNS) that can damage cellular components including lipids, proteins and DNA. This scavenging activity helps in reducing lipid peroxidation and maintaining cellular integrity under oxidative stress conditions (Liu *et al*., 2021; Iqbal *et al*., 2025).

In addition to direct radical scavenging, garlic enhances the body's endogenous antioxidant defense system through enzymatic antioxidant modulation. It has been shown to increase the activity of key antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPx), thereby strengthening the cellular defense mechanism against oxidative damage. Garlic compounds also help maintain intracellular glutathione levels, which is a critical determinant of redox balance. These combined effects contribute to the prevention of oxidative stress-related disorders such as cardiovascular diseases, neurodegenerative conditions and cancer (Shang *et al*., 2023; Kumar *et al*., 2024).

5.2 Antimicrobial activity

Garlic possesses strong antimicrobial properties against a wide range of pathogenic microorganisms, including bacteria, fungi, viruses and parasites. The antimicrobial efficacy is largely attributed to organosulfur compounds, particularly allicin, which exhibits broad-spectrum activity. Garlic extracts have been shown to be effective against both Gram-positive and Gram-negative bacteria, including antibiotic-resistant strains, making it a promising alternative to conventional antimicrobial agents (Borlinghaus *et al*., 2021; Cupertino *et al*., 2024). The antibacterial activity of garlic involves multiple mechanisms, including disruption of microbial cell membranes, inhibition of essential enzymes and interference with DNA and protein synthesis. Allicin reacts with thiol-containing enzymes in microorganisms, leading to the inactivation of metabolic pathways critical for survival. Similarly, garlic exhibits antifungal activity by inhibiting spore germination and altering membrane permeability in fungi such as *Candida* species. Its antiviral effects are associated with the inhibition of viral entry, replication and assembly, thereby reducing viral infectivity (El-Saadony *et al*., 2024; Chen *et al*., 2025).

Mechanistically, garlic compounds exert antimicrobial effects through cell membrane disruption and enzyme inhibition. The lipophilic nature of certain sulfur compounds allows them to penetrate microbial membranes, causing leakage of cellular contents and eventual cell death. Additionally, the interaction of these compounds with sulfhydryl groups of enzymes results in the inhibition of key metabolic processes, further enhancing their antimicrobial potency (Borlinghaus *et al*., 2021).

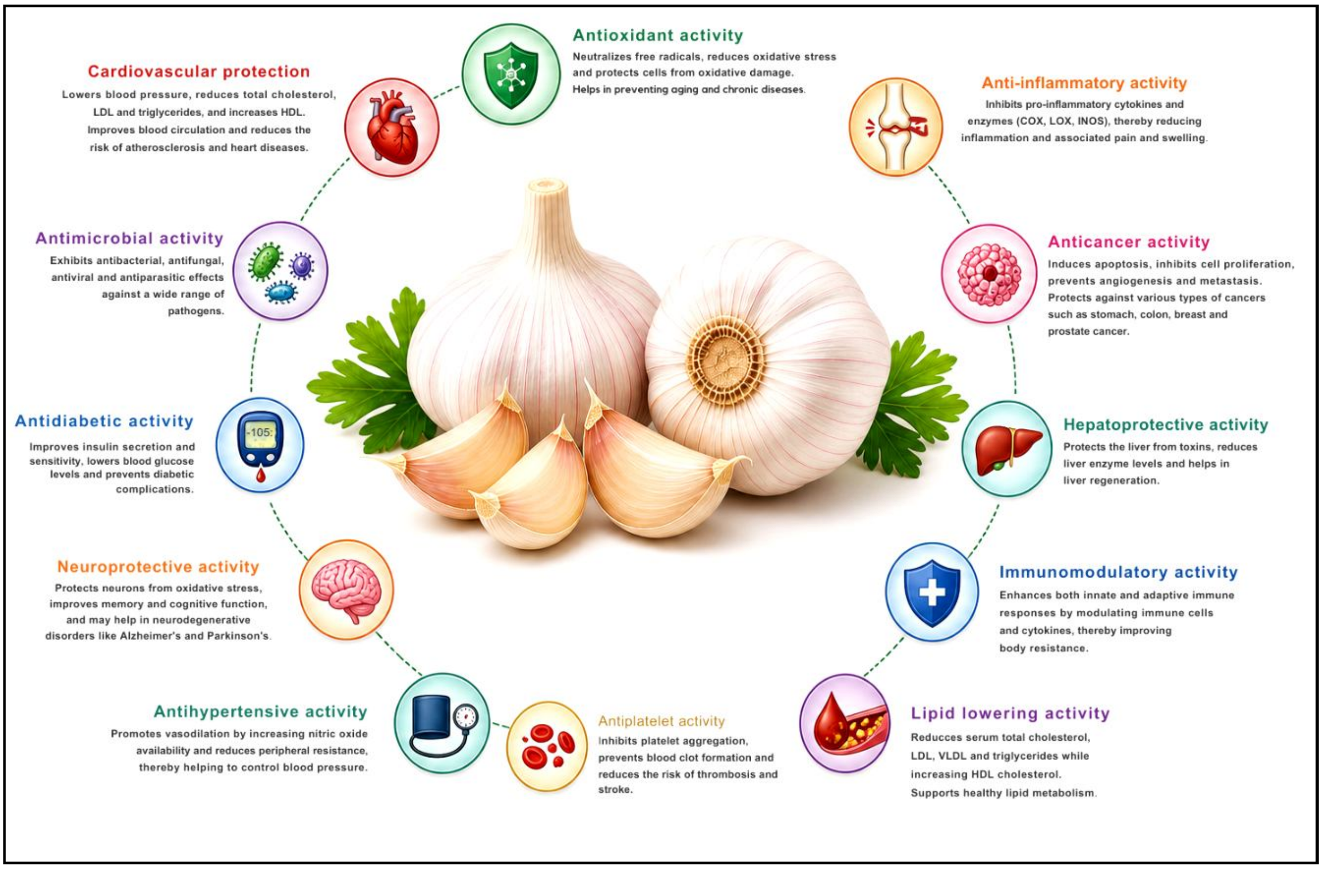

Figure 2: Pharmacological properties of garlic (Source: Prepared by us with the help of Biorender software).

5.3 Anti-inflammatory effects

Garlic also exhibits significant anti-inflammatory properties, which are crucial in the prevention and management of chronic inflammatory diseases. One of the primary mechanisms involves the modulation of cytokine production, where garlic compounds reduce the levels of pro-inflammatory cytokines such as tumor necrosis factor-alpha (TNF-α), interleukin-6 (IL-6) and interleukin-1β (IL-1β), while enhancing anti-inflammatory cytokines. This regulation helps in controlling excessive inflammatory responses and maintaining immune homeostasis (El-Saadony *et al*., 2024; Shang *et al*., 2023).

Another important mechanism underlying the anti-inflammatory activity of garlic is the inhibition of the nuclear factor-kappa B (NF-κB) signaling pathway, a key regulator of inflammation. Garlic-derived compounds, particularly allicin and S-allyl cysteine, suppress the activation of NF-κB, thereby reducing the expression of inflammatory mediators such as cyclooxygenase-2 (COX-2), inducible nitric oxide synthase (iNOS) and various cytokines. By targeting this pathway, garlic effectively attenuates inflammation at the molecular level and contributes to the prevention of diseases such as arthritis, cardiovascular disorders and metabolic syndrome (Kumar *et al*., 2024; Chen *et al*., 2025).

5.4 Cardioprotective effects

Garlic has been extensively studied for its cardioprotective potential, particularly in the prevention and management of cardiovascular diseases. One of its key mechanisms is lipid-lowering activity, where garlic compounds such as allicin and S-allyl cysteine inhibit enzymes involved in cholesterol biosynthesis, including HMG-CoA reductase. This results in reduced levels of total cholesterol, low-density lipoprotein (LDL) and triglycerides, while often improving high-density lipoprotein (HDL) levels. These lipid-modulating effects contribute significantly to reducing cardiovascular risk (Ried, 2020; Shang *et al*., 2023).

In addition, garlic plays an important role in blood pressure regulation. It promotes vasodilation by enhancing nitric oxide (NO) production and hydrogen sulfide (H_2S) signaling, leading to relaxation of vascular smooth muscles. Clinical studies have demonstrated that garlic supplementation can significantly reduce systolic and diastolic blood pressure, particularly in hypertensive individuals (Ried, 2020; Kumar *et al*., 2024). Garlic also exhibits anti-atherosclerotic effects, which involve inhibition of platelet aggregation, reduction of oxidative stress and prevention of endothelial dysfunction. Its antioxidant properties prevent the oxidation of LDL cholesterol, a key step in the development of atherosclerosis. Furthermore, garlic reduces plaque formation and improves arterial elasticity, thereby supporting overall cardiovascular health (El-Saadony *et al*., 2024).

5.5 Anticancer activity

Garlic has gained considerable attention for its anticancer properties, which are mediated through multiple cellular and molecular mechanisms. One of the primary actions is the induction of apoptosis (programmed cell death) in cancer cells. Organosulfur compounds such as diallyl disulfide (DADS) and diallyl trisulfide (DATS) activate intrinsic and extrinsic apoptotic pathways, leading to the elimination of malignant cells (Iciek *et al*., 2022; Shang *et al*., 2023). Garlic also exhibits strong anti-proliferative effects by inhibiting the growth and division of cancer cells. These effects are achieved through the modulation of cell cycle regulators and suppression of oncogenic signaling pathways. Garlic compounds interfere with DNA replication and protein synthesis, thereby limiting tumor progression.

In addition, garlic plays a chemopreventive role, reducing the initiation and development of cancer. It enhances the activity of detoxifying enzymes, neutralizes carcinogens and protects DNA from oxidative damage. Epidemiological studies suggest that regular consumption of garlic may lower the risk of cancers, particularly those of the gastrointestinal tract (Kumar *et al*., 2024; Rajpoot *et al*., 2026).

5.6 Antidiabetic activity

Garlic has demonstrated promising effects in the management of diabetes mellitus through its ability to regulate glucose metabolism. One of its primary actions is blood glucose regulation, where garlic compounds enhance glucose uptake and reduce hepatic glucose production. Allicin and related sulfur compounds play a significant role in improving glycemic control (Singh *et al*., 2025). Another important mechanism is the improvement of insulin sensitivity. Garlic enhances insulin secretion from pancreatic â-cells and improves insulin receptor function, thereby facilitating efficient glucose utilization. Additionally, its antioxidant properties help reduce oxidative stress associated with diabetes, which is a major factor in the development of complications such as neuropathy and nephropathy (Kumar *et al*., 2024).

5.7 Neuroprotective effects

Garlic exhibits significant neuroprotective properties, making it a potential candidate for the prevention and management of neurodegenerative disorders. Its anti-neuroinflammatory actions involve the suppression of inflammatory mediators and reduction of oxidative stress in neural tissues. Garlic compounds inhibit microglial activation and decrease the production of pro-inflammatory cytokines in the brain, thereby protecting neuronal cells (Shang *et al*., 2023). Furthermore, garlic contributes to cognitive protection by enhancing neuronal survival, improving synaptic plasticity and reducing neurotoxicity. Its antioxidant and anti-inflammatory properties help prevent the accumulation of toxic proteins such as beta-amyloid, which are associated with conditions like Alzheimer's disease. These effects highlight its potential role in maintaining brain health and cognitive function (Kumar *et al*., 2024).

5.8 Hepatoprotective and renoprotective effects

Garlic plays a crucial role in protecting vital organs such as the liver and kidneys from toxic damage. Its hepatoprotective effects are primarily mediated through antioxidant activity and enhancement of detoxification pathways. Garlic stimulates phase I and phase II detoxifying enzymes, facilitating the elimination of toxins and reducing oxidative damage in liver tissues. It also helps in maintaining normal liver enzyme levels and preventing lipid accumulation in hepatic cells (El-Saadony *et al*., 2024). Similarly, garlic exhibits renoprotective effects by protecting kidney tissues from oxidative stress and inflammation. It improves renal function by reducing lipid peroxidation, enhancing antioxidant enzyme activity and preventing structural damage to nephrons. Garlic has also been shown to mitigate nephrotoxicity induced by drugs and environmental toxins, highlighting its role in maintaining renal health.

6. Mechanisms of action of garlic

The diverse pharmacological effects of garlic arise from its ability to interact with multiple molecular targets and regulate key biochemical pathways at the cellular and systemic levels. These mechanisms are largely mediated by its bioactive constituents particularly organosulfur compounds which influence enzyme activity, receptor signaling, gene expression and redox homeostasis. Rather than acting through a single pathway, garlic exhibits a multi-target mode of action, making it especially effective in complex diseases involving oxidative stress, inflammation and metabolic dysregulation (Shang *et al*., 2023; El-Saadony *et al*., 2024).

6.1 Molecular targets

Garlic-derived compounds interact with a wide range of molecular targets, including enzymes and cell surface or intracellular receptors. One of the key mechanisms involves the modification of thiol-containing enzymes by reactive sulfur compounds such as allicin. These compounds form disulfide bonds with cysteine residues in enzymes, leading to changes in enzyme activity. For instance, garlic inhibits HMG-CoA reductase, a key enzyme in cholesterol biosynthesis, thereby contributing to lipid-lowering effects. It also modulates enzymes such as cyclooxygenase (COX) and lipoxygenase (LOX), which are involved in inflammatory responses (Iciek *et al*., 2022; Kumar *et al*., 2024).

Garlic compounds also interact with various receptors, including peroxisome proliferator-activated receptors (PPARs), which play a role in lipid metabolism and insulin sensitivity. Activation of PPAR-γ by garlic constituents enhances glucose uptake and improves metabolic regulation. Additionally, garlic influences endothelial nitric oxide synthase (eNOS), leading to increased nitric oxide production and improved vascular function. These interactions highlight the ability of garlic to modulate both metabolic and cardiovascular pathways at the receptor level (Ried, 2020; Shang *et al*., 2023).

6.2 Signal transduction pathways

Garlic bioactives regulate several critical signal transduction pathways that control inflammation, oxidative stress, cell survival and apoptosis. One of the most important pathways affected is the nuclear factor-kappa B (NF-κB) pathway, a central regulator of inflammatory responses. Garlic compounds inhibit the activation of NF-κB, thereby reducing the expression of pro-inflammatory cytokines, adhesion molecules and enzymes such as inducible nitric oxide synthase (iNOS) (El-Saadony *et al*., 2024). Another key pathway modulated by garlic is the mitogen-activated protein kinase (MAPK) pathway, which is involved in cell proliferation, differentiation and stress responses. Garlic constituents can regulate MAPK signaling, leading to inhibition of tumor growth and inflammation. Furthermore, garlic activates the Nrf2 (nuclear factor erythroid 2-related factor 2) pathway, which enhances the expression of antioxidant response elements (ARE) and promotes the synthesis of detoxifying and antioxidant enzymes such as glutathione S-transferase and heme oxygenase-1. This activation plays a crucial role in cellular defense against oxidative stress (Liu *et al*., 2021; Shang *et al*., 2023). Garlic also influences apoptotic pathways, including both intrinsic (mitochondrial) and extrinsic pathways. It regulates proteins such as Bcl-2, Bax and caspases, thereby promoting programmed cell death in cancer cells while protecting normal cells from damage.

6.3 Gene expression modulation

Garlic has the ability to modulate gene expression through epigenetic and transcriptional mechanisms. Its bioactive compounds influence the expression of genes involved in antioxidant defense, inflammation, lipid metabolism and apoptosis. For example, garlic upregulates genes encoding antioxidant enzymes such as superoxide dismutase (SOD), catalase and glutathione peroxidase, enhancing cellular protection against oxidative damage (Kumar *et al*., 2024). In addition, garlic downregulates the expression of genes associated with inflammation, including those encoding tumor necrosis factor-alpha (TNF-α), interleukin-6 (IL-6) and cyclooxygenase-2 (COX-2). It also modulates genes involved in lipid metabolism, thereby reducing cholesterol synthesis and improving lipid profiles. Emerging studies suggest that garlic may exert epigenetic effects by influencing DNA methylation and histone modification, which further regulate gene expression and cellular function (Shang *et al*., 2023).

6.4 Role of organosulfur compounds

Organosulfur compounds are central to the biological activity of garlic and play a pivotal role in its mechanisms of action. Compounds such as allicin, diallyl disulfide (DADS), diallyl trisulfide (DATS) and S-allyl cysteine (SAC) exhibit high reactivity due to the presence of sulfur atoms, enabling them to interact with cellular proteins, enzymes and signaling molecules. These compounds can modify thiol groups in proteins, alter redox balance and regulate signal transduction pathways (Iciek *et al*., 2022). Allicin, in particular, acts as a reactive sulfur species that can penetrate cell membranes and interact with intracellular targets, leading to antimicrobial and anticancer effects. DATS and DADS are known to induce apoptosis and inhibit tumor growth, while SAC exhibits strong antioxidant and cardioprotective properties with greater stability and bioavailability. The combined action of these compounds results in a synergistic effect that enhances the overall therapeutic potential of garlic (Liu *et al*., 2021; El-Saadony *et al*., 2024).

7. Therapeutic applications of garlic

Garlic has transitioned from a traditional household remedy to a scientifically validated therapeutic agent with applications across a wide spectrum of chronic and infectious diseases. Its efficacy is attributed to the synergistic action of organosulfur compounds, phenolics and other bioactive constituents that target multiple physiological pathways. The therapeutic applications of garlic are particularly significant in the management of chronic diseases such as cardiovascular disorders, diabetes and cancer, as well as in its integration into both traditional and modern medical systems (Table 3 and Figure 3).

Table 3: Extraction techniques for garlic bioactive compounds

Extraction method	Principle	Advantages	Limitations	References
Soxhlet extraction	Continuous solvent extraction	Efficient for lipid compounds	Time-consuming, high solvent use	Deepa *et al*., 2022
Ultrasound-assisted extraction (UAE)	Acoustic cavitation	Faster, higher yield	Equipment cost	Chemat *et al*., 2022
Microwave-assisted extraction (MAE)	Microwave heating	Rapid extraction, energy-efficient	Thermal degradation risk	Chen *et al*., 2023
Supercritical fluid extraction (SFE)	CO_2 -based extraction	Solvent-free, high purity	Expensive setup	Pourmortazavi *et al*., 2021
Enzyme-assisted extraction	Enzymatic cell wall degradation	High selectivity	Cost of enzymes	Nadar *et al*., 2021

7.1 Role in chronic diseases

Garlic plays a critical role in the prevention and management of cardiovascular diseases (CVD) through its lipid-lowering, antihypertensive and antiplatelet effects. Regular consumption of garlic has been associated with reductions in total cholesterol, low-density lipoprotein (LDL) and triglycerides, while improving high-density lipoprotein (HDL) levels. Additionally, garlic enhances nitric oxide production, leading to vasodilation and improved blood flow. These effects collectively reduce the risk of atherosclerosis, hypertension and coronary artery disease (Ried, 2020; Shang *et al*., 2023). In the context of diabetes mellitus, garlic exhibits hypoglycemic properties by improving insulin sensitivity, enhancing glucose uptake and reducing hepatic glucose production. It also mitigates oxidative stress and inflammation associated with diabetic complications. Studies have shown that garlic supplementation can significantly lower fasting blood glucose levels and improve glycemic control, making it a valuable adjunct in diabetes management (Singh *et al*., 2025; Kumar *et al*., 2024).

Garlic's role in cancer prevention and therapy has gained increasing attention. Its bioactive compounds inhibit tumor initiation, progression and metastasis through mechanisms such as apoptosis induction, anti-proliferative effects and modulation of carcinogen metabolism. Garlic also enhances detoxification pathways and protects DNA from oxidative damage. Epidemiological studies suggest that higher garlic intake is associated with reduced risk of certain cancers, particularly gastrointestinal cancers (Rajpoot *et al*., 2026; Iciek *et al*., 2022).

7.2 Use in traditional and modern medicine

Garlic has been extensively used in traditional medicine systems such as Ayurveda, Traditional Chinese Medicine and Unani medicine for centuries. In Ayurveda, garlic is regarded as a rejuvenating agent (rasayana) and is used to treat respiratory disorders, digestive issues, infections and cardiovascular conditions. Similarly, in Traditional Chinese Medicine, garlic is used to improve digestion, combat infections and enhance circulation. In modern medicine, garlic is increasingly recognized as a complementary and alternative therapeutic agent. It is incorporated into nutraceutical formulations and dietary supplements aimed at improving cardiovascular health, boosting immunity and reducing inflammation. The growing interest in plant-based therapies and functional foods has further strengthened the role of garlic in integrative medicine, where it is used alongside conventional treatments to enhance therapeutic outcomes (El-Saadony *et al*., 2024; Shang *et al*., 2023)

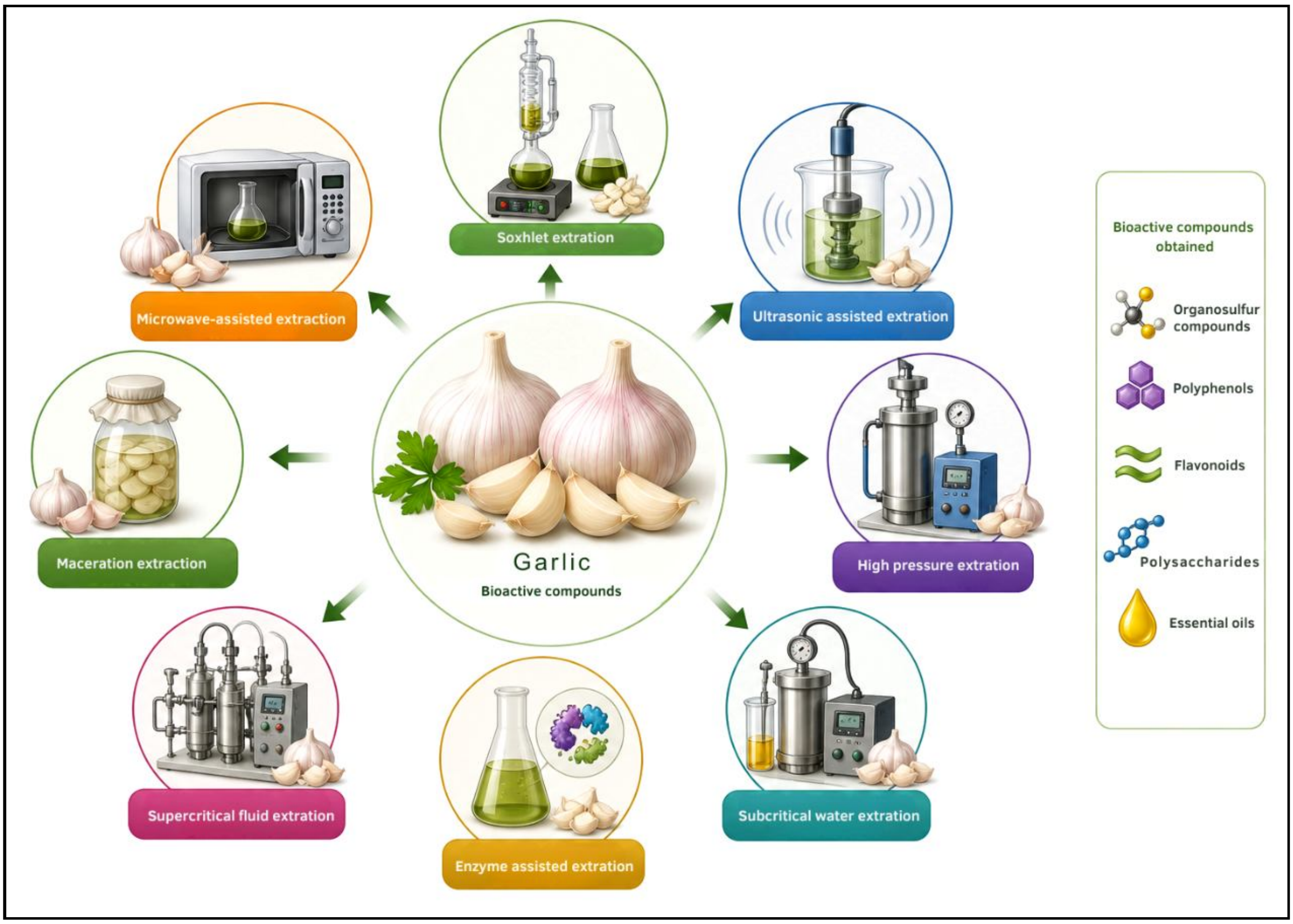

Figure 3: Extraction techniques for garlic bioactive compounds (Source: Prepared by us with the help of Biorender software).

7.3 Clinical studies and human trials

Numerous clinical studies and human trials have evaluated the efficacy of garlic in various health conditions. Randomized controlled trials have demonstrated that garlic supplementation can significantly reduce blood pressure in hypertensive patients, with effects comparable to standard antihypertensive drugs in some cases (Ried, 2020). Similarly, clinical studies have reported reductions in serum cholesterol levels and improvements in lipid profiles following garlic intake. In diabetes research, clinical trials have shown that garlic supplementation improves fasting blood glucose levels and insulin sensitivity. In addition, studies investigating its anticancer potential suggest that garlic consumption may reduce cancer risk, although more large-scale, long-term clinical trials are needed to confirm these findings. Overall, while clinical evidence supports many of garlic's therapeutic benefits, variability in study design, dosage and formulation highlights the need for standardized protocols and further research (Kumar *et al*., 2024; Rajpoot *et al*., 2026).

7.4 Dosage forms

Garlic is available in various dosage forms, each differing in composition, stability and bioavailability. Raw garlic is the most traditional form and contains active compounds such as allicin, which is formed upon crushing or chopping. However, its strong odor and potential gastrointestinal irritation may limit its acceptability. Aged garlic extract (AGE) is a processed form obtained by aging garlic in ethanol over an extended period. This process converts unstable compounds into more stable and bioavailable forms such as S-allyl cysteine, which exhibit enhanced antioxidant and cardioprotective effects with reduced toxicity. AGE is widely used in clinical studies due to its standardized composition and improved tolerability (Amagase, 2020).

Garlic is also available as dietary supplements in the form of capsules, tablets, powders and oils. These formulations are designed to provide consistent dosages and improved convenience. However, the efficacy of these supplements depends on factors such as preparation method, concentration of active compounds and bioavailability. Standardization of garlic products remains a critical issue to ensure consistent therapeutic outcomes.

8. Toxicity and safety considerations of garlic

Garlic is generally regarded as safe and well tolerated when consumed as part of a normal diet; however, its use in concentrated forms (extracts, oils, or high-dose supplements) requires careful consideration of dose, preparation and patient context. Safety is influenced by the form of garlic (raw, powder, oil, aged extract), the concentration of bioactive organosulfur compounds and individual susceptibility. While most adverse effects are mild and reversible, clinically relevant interactions and dose-related toxicities can occur, particularly with long-term or high-dose intake.

8.1 Safe dosage levels

For healthy adults, commonly cited dietary intake ranges of garlic include approximately 1-2 fresh cloves per day (3-5 g), which are generally considered safe and beneficial. In supplement form, standardized preparations such as garlic powder, oil, or aged garlic extract (AGE) are typically administered in doses equivalent to 600-1200 mg/day of garlic powder or 1.2-2.4 g/day of AGE, divided into multiple doses. Clinical studies using AGE often employ doses around 600-1200 mg/day with good tolerability (Ried, 2020; Amagase, 2020). It is important to note that the effective dose depends on the content of active constituents (*e.g*., allicin yield or S-allyl cysteine levels) and standardized formulations are preferred for consistency. Higher intakes may be used in research settings, but routine consumption beyond recommended levels is not advised without medical supervision. Special populations such as pregnant or lactating women, children and individuals with bleeding disorders should use garlic supplements cautiously and under professional guidance.

8.2 Side effects

The most common adverse effects of garlic are gastrointestinal disturbances, including nausea, abdominal discomfort, bloating, flatulence and heartburn. These effects are more likely with raw garlic or high-dose supplements due to the irritant nature of certain sulfur compounds, particularly allicin. Enteric-coated formulations and aged garlic extracts tend to be better tolerated. Garlic can also cause allergic reactions in sensitive individuals. These may manifest as contact dermatitis (especially in food handlers), skin rashes, or, rarely, respiratory symptoms. Topical exposure to crushed garlic has been associated with chemical burns and skin irritation due to its sulfur content. Additionally, garlic consumption is commonly associated with halitosis (garlic breath) and body odor, which, while not harmful, may affect compliance.

8.3 Drug interactions

Garlic has clinically relevant drug interaction potential, primarily due to its antiplatelet and mild anticoagulant effects. It can increase bleeding risk when taken concomitantly with anticoagulant or antiplatelet medications such as warfarin, aspirin, clopidogrel and novel oral anticoagulants. Patients scheduled for surgery are often advised to discontinue high-dose garlic supplements at least 7-10 days prior to reduce bleeding risk (Ried, 2020). Garlic may also interact with drugs metabolized by cytochrome P450 enzymes, potentially altering their bioavailability. Interactions have been reported with certain antiretroviral drugs (*e.g*., saquinavir), where garlic supplements reduced plasma drug levels. Additionally, additive effects may occur with antihypertensive and antidiabetic medications, potentially enhancing their actions and requiring dose monitoring to avoid hypotension or hypoglycemia.

8.4 Toxicological studies

Toxicological evaluations of garlic in animal and human studies generally support its safety at commonly consumed levels. Acute toxicity studies indicate a high margin of safety, with adverse effects occurring only at very high doses. However, subchronic and chronic exposure to excessive amounts of garlic extracts has been associated with organ-specific changes in experimental models, including alterations in liver enzyme activity and mild gastrointestinal irritation (El-Saadony *et al*., 2024; Kumar *et al*., 2024). Certain preparations, particularly garlic oil and concentrated extracts, may pose a higher risk of toxicity if not properly standardized. Raw garlic in excessive amounts has been associated with gastric mucosal irritation and, in rare cases, anemia due to oxidative damage to red blood cells in animal studies. Conversely, aged garlic extract has demonstrated a favorable safety profile due to the presence of more stable and less reactive compounds such as S-allyl cysteine. Overall, current toxicological evidence suggests that garlic is safe when consumed within recommended limits, but caution is warranted with high-dose supplementation, prolonged use and in individuals with underlying medical conditions or concurrent medication use.

9. Processing and value addition of garlic

Processing plays a decisive role in determining the stability, composition and bioactivity of garlic-derived products. Because many key compounds in garlic especially allicin are chemically unstable, different processing routes are used to tailor shelf-life, sensory properties and therapeutic efficacy. Value addition not only improves marketability and convenience but also enables the development of standardized products for food, pharmaceutical and nutraceutical applications.

9.1 Garlic oil, powder and extracts

Garlic is commonly processed into garlic oil, garlic powder and various extracts, each with distinct chemical profiles and applications. Garlic powder, produced by drying and pulverizing cloves, is widely used in the food industry as a flavoring agent due to its extended shelf life and ease of handling. Although, drying reduces some volatile sulfur compounds, it retains a significant portion of stable constituents, making it suitable for both culinary and nutraceutical uses (Shang *et al*., 2023). Garlic oil is obtained through steam distillation or solvent extraction and is rich in lipid-soluble sulfur compounds such as diallyl disulfide and diallyl trisulfide. These compounds contribute to antimicrobial and antioxidant activities but differ from fresh garlic in composition due to the loss of allicin during processing. Oil-based preparations are commonly used in pharmaceutical and cosmetic formulations because of their stability and ease of incorporation. Garlic extracts can be broadly categorized into aqueous, ethanol and oil-based extracts, each differing in bioactive composition. Aqueous extracts retain water-soluble compounds like S-allyl cysteine, whereas organic solvent extracts are enriched in lipid-soluble sulfur compounds. The choice of extraction method significantly influences the biological activity and therapeutic potential of the final product (Liu *et al*., 2021; El-Saadony *et al*., 2024).

9.2 Aged garlic extract

Aged garlic extract (AGE) is one of the most extensively studied and commercially important garlic products. It is prepared by aging sliced garlic in aqueous ethanol over extended periods, typically 10-20 months. This process converts unstable and reactive compounds such as allicin into more stable, water-soluble compounds including S-allyl cysteine (SAC) and S-allyl mercaptocysteine (SAMC). These compounds exhibit high bioavailability, strong antioxidant activity and reduced toxicity compared to raw garlic components (Amagase, 2020). AGE is widely used in clinical research due to its standardized composition and consistent pharmacological effects. It has demonstrated significant benefits in cardiovascular health, immune modulation and oxidative stress reduction. Additionally, AGE has a milder odor and improved gastrointestinal tolerability, enhancing patient compliance and acceptability.

9.3 Impact of processing on bioactivity

Processing methods have a profound impact on the bioactivity of garlic, particularly due to the instability of allicin and the transformation of sulfur compounds. Mechanical disruption, such as crushing or chopping, is essential for the enzymatic conversion of alliin to allicin. However, thermal processing (boiling, frying, roasting) can inactivate alliinase, thereby reducing allicin formation and altering the phytochemical profile. Interestingly, certain processing techniques may enhance the availability of more stable compounds. For example, aging increases the concentration of water-soluble antioxidants, while controlled heating may reduce pungency and improve palatability without completely eliminating bioactivity. Drying methods (freeze-drying vs. oven-drying) also influence the retention of bioactive compounds. Overall, the biological efficacy of garlic products depends on a balance between preserving reactive compounds and generating stable derivatives with sustained activity (Shang *et al*., 2023; El-Saadony *et al*., 2024).

10. Industrial and nutraceutical applications of garlic

The multifunctional properties of garlic have led to its widespread application across food, pharmaceutical and cosmetic industries. Its natural origin, safety profile and broad-spectrum biological activities make it a valuable ingredient in the development of functional products and value-added formulations.

10.1 Functional foods

Garlic is extensively used in the formulation of functional foods, which are designed to provide health benefits beyond basic nutrition. It is incorporated into products such as fortified oils, health beverages, dietary seasonings and ready-to-eat foods. Garlic-enriched foods are promoted for their ability to support cardiovascular health, enhance immunity and reduce oxidative stress. Its prebiotic components, particularly fructans, also contribute to gut health by promoting beneficial microbiota. The inclusion of garlic in functional foods aligns with the growing consumer demand for natural, plant-based ingredients with scientifically validated health benefits. Food industries are increasingly focusing on optimizing garlic processing techniques to retain bioactive compounds while improving sensory qualities.

10.2 Pharmaceutical formulations

In the pharmaceutical sector, garlic is utilized in the development of therapeutic formulations such as capsules, tablets, syrups and standardized extracts. These formulations are designed to deliver consistent doses of bioactive compounds for the management of conditions such as hypertension, hyperlipidemia, diabetes and infections. Garlic-derived compounds are also being explored for their role in drug development, particularly as antimicrobial and anticancer agents. Advanced delivery systems, including nanoencapsulation and controlled-release formulations, are being investigated to enhance the stability, bioavailability and targeted delivery of garlic bioactives. These innovations aim to overcome limitations associated with the instability and rapid metabolism of compounds like allicin, thereby improving therapeutic outcomes (El-Saadony *et al*., 2024).

10.3 Cosmeceutical uses

Garlic has also found applications in the cosmeceutical industry, where it is used in products for skin and hair care. Its antimicrobial and antioxidant properties make it effective in treating acne, preventing skin infections and reducing signs of ageing. Garlic extracts are incorporated into topical formulations such as creams, gels and lotions to promote skin health and wound healing. In hair care, garlic is used in formulations aimed at reducing hair loss and promoting hair growth, owing to its ability to improve blood circulation and provide essential nutrients to hair follicles. Additionally, its antifungal properties are beneficial in managing scalp conditions such as dandruff.

11. Recent advances and emerging trends

Rapid progress in materials science, biotechnology and systems biology has reshaped how garlic bioactives are formulated, delivered and studied. These advances aim to overcome intrinsic limitations such as instability of key compounds and variable bioavailability while enabling precise, mechanism-driven applications. Nanotechnology-based approaches are being actively developed to improve the stability and targeted delivery of garlic-derived compounds. Nanoencapsulation, liposomes, solid lipid nanoparticles, nanoemulsions and polymeric nanoparticles can protect labile molecules (*e.g*., allicin) from premature degradation, enhance permeability across biological membranes and allow controlled release. Encapsulating garlic oil or purified organosulfur compounds has been shown to increase antimicrobial efficacy, prolong antioxidant activity and reduce dose-related irritation. Targeted systems (*e.g*., ligand-decorated nanoparticles) are also under investigation for site-specific delivery in cancer and cardiovascular applications, where localized concentration and reduced systemic exposure are desirable. In addition, food-grade nanoemulsions are being explored for functional foods, enabling better dispersion, improved sensory acceptance and enhanced intestinal absorption of lipophilic constituents (El-Saadony *et al*., 2024; Kumar *et al*., 2024). The application of omics technologies has deepened understanding of garlic biology and its therapeutic mechanisms. Genomics and transcriptomics are being used to identify genes involved in sulfur assimilation, alliin biosynthesis and stress responses, supporting marker-assisted selection and breeding for high-bioactive cultivars. Metabolomics enables comprehensive profiling of volatile and non-volatile compounds, revealing how genotype, environment and processing shape the phytochemical spectrum. These approaches also help link specific metabolites to biological activities through pathway analysis. Proteomics complements this by identifying protein targets and signaling cascades modulated by garlic compounds. Together, multi-omics integration is uncovering networks that explain variability in efficacy and is guiding precision formulation and cultivar development (Shang *et al*., 2023; Liu *et al*., 2021). A major focus of current research is improving the bioavailability of garlic bioactives. Strategies include standardization of extracts (*e.g.,* aged garlic extract enriched in S-allyl cysteine), encapsulation technologies to protect compounds during digestion and co-delivery with bioenhancers that improve absorption and metabolic stability. Controlled-release formulations and enteric coatings are used to bypass gastric degradation and target intestinal uptake. Fermentation and enzymatic processing are also being explored to convert precursors into more stable, absorbable derivatives. These approaches aim to achieve consistent plasma levels, reduce inter-individual variability and translate *in vitro* efficacy into reliable clinical outcomes (Amagase, 2020; El-Saadony *et al*., 2024).

12. Challenges and limitations

Despite promising advances, several scientific and practical challenges limit the full clinical translation of garlic-based interventions. One of the primary limitations is the variability in phytochemical composition, influenced by cultivar, soil type, climate, agronomic practices, harvest maturity and storage conditions. Processing methods (drying, heating, extraction) further alter the chemical profile. This variability leads to inconsistent biological effects across studies and products, complicating dose standardization and comparison of outcomes. Developing chemically standardized preparations and robust quality-control markers (*e.g*., allicin yield or S-allyl cysteine content) remains essential (Shang *et al*., 2023). Allicin, the signature bioactive formed upon tissue disruption, is highly unstable and rapidly decomposes into secondary sulfur compounds. While these derivatives also possess biological activity, their effects differ in potency and mechanism. Thermal processing can inactivate alliinase, reducing allicin formation, whereas prolonged storage can shift the compound profile toward more stable but less reactive species. Ensuring stability during processing, storage and delivery is a persistent challenge and a key driver behind the adoption of encapsulation and aged extracts (Borlinghaus *et al*., 2021; Amagase, 2020). Although, numerous clinical studies suggest benefits in cardiovascular, metabolic and inflammatory conditions, there is a lack of standardized clinical data due to heterogeneity in study design, sample size, duration and garlic preparations used (raw, powder, oil, aged extract). Differences in dosing metrics (*e.g*., weight vs. allicin yield vs. SAC content) further hinder cross-study comparisons. Large, well-designed randomized controlled trials with standardized formulations and biomarkers are needed to establish definitive efficacy, optimal dosing and long-term safety profiles (Ried, 2020; Kumar *et al*., 2024).

13. Future perspectives

The expanding body of scientific evidence surrounding garlic highlights its immense potential as a multifunctional therapeutic agent. However, to fully translate this potential into practical and clinically accepted applications, several key areas require focused attention and advancement. One of the most critical future directions is the need for rigorous clinical validation. Although, numerous experimental and preliminary clinical studies have demonstrated promising pharmacological effects, there remains a lack of large-scale, well-designed randomized controlled trials. Future research should emphasize standardized study designs, clearly defined dosage regimens and consistent formulations to ensure reproducibility and comparability of results. Establishing strong clinical evidence will be essential for gaining wider acceptance of garlic-based therapies in mainstream medicine and for defining precise therapeutic indications. Another important area is genetic improvement for enhanced bioactive content. The variability in phytochemical composition among garlic cultivars presents both a challenge and an opportunity. Advances in plant breeding, molecular biology and biotechnology can be utilized to develop improved varieties with higher concentrations of key bioactive compounds such as organosulfur metabolites. Marker-assisted selection, genome editing and tissue culture techniques offer promising tools for enhancing yield, disease resistance and phytochemical quality. Developing standardized, high-quality cultivars will not only improve therapeutic consistency but also support large-scale industrial applications. The integration of garlic into modern healthcare systems represents a significant step toward bridging traditional knowledge and contemporary medicine. Garlic has long been used in traditional healing systems and its incorporation into evidence-based healthcare frameworks could provide complementary and preventive therapeutic options. This integration requires the development of standardized formulations, regulatory approval and clinical guidelines for safe and effective use. Additionally, interdisciplinary collaboration among researchers, clinicians and policymakers will be essential to promote the rational use of garlic in healthcare. Public awareness and education regarding its benefits and limitations will further support its acceptance as a functional food and therapeutic agent. Looking ahead, the future of garlic research lies in combining traditional wisdom with advanced scientific approaches. Innovations in formulation technologies, improved understanding of molecular mechanisms and personalized nutrition strategies may further enhance its applicability. By addressing current limitations and focusing on evidence-based development, garlic has the potential to emerge as a key component in preventive medicine, sustainable healthcare and nutraceutical innovation.

14. Conclusion

A. sativum is a highly valuable functional food with a rich phytochemical profile, particularly organosulfur compounds, that underpins its wide range of pharmacological activities. Extensive evidence highlights its antioxidant, antimicrobial, anti-inflammatory, cardioprotective, anticancer, antidiabetic, neuroprotective and organ-protective effects, validating its traditional use in medicine. Its versatility in various processed forms and applications in nutraceutical, pharmaceutical and cosmeceutical industries further enhances its significance. Despite these promising attributes, challenges such as variability in bioactive composition, instability of key compounds like allicin and limited standardized clinical data restrict its full therapeutic translation. Future research should focus on well-designed clinical trials, standardized formulations and advanced delivery systems to improve efficacy and reproducibility.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article.

References

Amagase, H. (2020). Clarifying the real bioactive constituents of garlic. The Journal of Nutrition, **150(Suppl 1)**:100-102.

Amer, A.; Saad, K. and El-Gamal, M. (2025). Processing effects on garlic compounds. Food Chemistry Advances, **4**:100201.

Ansary, J.; Forbes-Hernandez, T. Y.; Gil, E.; Cianciosi, D.; Zhang, J.; Elexpuru-Zabaleta, M.; Simal-Gandara, J. and Giampieri, F. (2020). Potential health benefit of garlic based on human intervention studies. Antioxidants, **9(7)**:619.

Batiha, G. E.-S.; Beshbishy, A. M.; Wasef, L. G.; Elewa, Y. H. A.; Al-Sagan, A. A.; Abd El-Hack, M. E.; Taha, A. E.; Abd-Elhakim, Y. M. and Prasad Devkota, H. (2020). Chemical constituents and pharmacological activities of garlic. Nutrients, **12(3)**:872.

Bi, X. and Usha, P. (2021). Comparative composition of *Allium* species. Journal of Agricultural Science, **13(4)**:123-130.

Block, E. (2020). Garlic and other *Allium*: The science and lore. Royal Society of Chemistry, **3**:1400.

Borlinghaus, J.; Albrecht, F.; Gruhlke, M. C. H.; Nwachukwu, I. D. and Slusarenko, A. J. (2021). Allicin: Chemistry and biological properties. Molecules, **26(9)**:2670.

Choudhary, S.; Noor, M. U.; Hussain, M. S.; Mishra, M. and Tyagi, S. (2022). Therapeutic uses and pharmacological properties of garlic. Journal of Herbal Science, **9(3)**:45-59.

Dashak, D. A. and Nwinuka, N. M. (2020). Nutritional evaluation of garlic. African Journal of Food Science, **14(3)**:45-52.

El-Saadony, M. T.; Saad, A. M.; El-Tahan, A. M.; Sayed, S. F.; Taha, A. E.; Ramadan, M. M. and Abd El-Mageed, T. A. (2024). Health-promoting properties of garlic. Frontiers in Immunology, **15**:1277074.

El-Tahan, A. M.; Ramadan, M. M. and Taha, A. E. (2024). Garlic immune modulation. Frontiers in Immunology, **15**:1277074.

Fernandez, M. L.; Ried, K.; Varady, K. A. and Jones, P. J. H. (2025). Nutritional benefits of garlic. Foods, **14(3)**:512.

Gan, R.; Corke, H. and Li, H. (2023). Functional phytochemicals in garlic. Food Science Advances, **5(2)**:88-102.

Gupta, R.; Singh, P.; Sharma, V.; Yadav, M.; Kumar, A. and Verma, D. (2024). Nutritional and phytochemical evaluation of garlic. Journal of Food Composition and Analysis, **115**:104912.

Hossain, M. A.; Rahman, M. S. and Uddin, M. J. (2023). Functional properties of garlic compounds. Food Research International, **165**:112345.

Iciek, M.; Kwiecień, I.; W³odek, L.; Bilska-Wilkosz, A. and Kowalczyk-Pachel, D. (2022). Biological properties of organosulfur compounds. Environmental and Molecular Mutagenesis, **63(3)**:245-257.

Iqbal, U. Z.; Gillani, S. F.; Shahid, S.; Iftikhar, M.; Shehzadi, I.; Yousaf, R.; Ali, R.; Akhtar, G.; Tehreem and Arfa (2025). Phytochemical screening and antioxidant activity of garlic. Nutritional Foundations of Holistic Health, pp:191-198.

Kamenetsky, R.; Rabinowitch, H. D.; Kik, C. and Goldman, I. L. (2021). Garlic: Botany and horticulture. Horticultural Reviews, **48**:1-54.

Kaur, H.; Singh, J. and Sharma, P. (2026). Garlic anticancer mechanisms. Cancer Research Reviews, **15**:100345.

Kumar, S.; Yadav, R.; Verma, A.; Singh, D.; Patel, M. and Sharma, R. (2024). Pharmacological potential of garlic. Journal of Herbal Medicine, **38**:100637.

Li, W.; Zhang, J. and Chen, M. (2021). Molecular classification of *Allium* species. Plant Biology Journal, **23(4)**:445-456.

Liu, J.; Zhang, X.; Wang, Z.; Li, P.; Zhao, M. and Chen, W. (2021). Advances in garlic polysaccharides and their biological activities. International Journal of Biological Macromolecules, **182**:129-139.

Mavumengwana, V. and Tang, G. (2023). Bioactive sulfur compounds in garlic. Plant Foods for Human Nutrition, **78**:234-245.

Okoro, B. C.; Okechukwu, I.; Okafor, U. and Eze, N. (2023). Ethnobotanical and bioactive importance of garlic. Journal of Herbal Medicine, **37**:100623.

Otunola, G. A. and Afolayan, A. J. (2020). Nutritional composition of garlic bulbs. Food Chemistry Reports, **2**:100012.

Oyaluna, Z. E.; Martinez, C.; Gomez, L. and Herrera, D. (2024). Chemical analysis of alliin-rich garlic extract. Journal of Food Biochemistry, **48(5)**:e13901.

Ozma, M. A.; Abbasi, A.; Rezaee, M. A.; Hosseini, H.; Hosseinzadeh, N. and Sabahi, S. (2023). Nutritional and medicinal profile of garlic. Food Reviews International, **39**:6324-6361.

Patel, M.; Singh, D. and Verma, A. (2024). Garlic pharmacology review. Journal of Medicinal Plants, **18(3)**:210-225.

Rahman, M. A.; Hussain, Z. and Shah, F. (2025). Garlic cardiovascular effects. Nutrients, **17**:455-468.

Rajpoot, R.; Sharma, P.; Kaur, H.; Singh, J. and Kaur, M. (2026). Chemopreventive role of garlic. Journal of Functional Foods, **102**:105432.

Ried, K.; Travica, N.; Sali, A. and Pipingas, A. (2020). Garlic lowers blood pressure: Meta-analysis. Experimental and Therapeutic Medicine, **19**:1472-1478.

Saad, A. M.; Sayed, S. F. and Abd El-Mageed, T. A. (2024). Garlic therapeutic mechanisms. Frontiers in Pharmacology, **15**:120345.

Salam, A. (2025). Molecular docking of garlic compounds. Research Journal of Pharmacy and Technology, **18(12)**:5678-5685.

Shang, A.; Cao, S.; Xu, X.; Gan, R.; Tang, G.; Corke, H.; Mavumengwana, V. and Li, H. (2023). Bioactive compounds and biological functions of garlic. Food Chemistry, **405**:134650.

Sharma, R. and Rao, K. S. (2023). Advances in garlic taxonomy. Plant Systematics Today, **10(2)**:67-78.

Simon, P. W.; Jenderek, M. M. and Kamenetsky, R. (2020). Garlic origin and domestication. USDA Vegetable Crops Review, **6**:1-50.

Singh, N.; Sharma, A.; Verma, P.; Mishra, S. and Patel, R. (2025). Therapeutic versatility of *Allium* species. Environmental Science and Pollution Research, **32**:14567-14589.

Singh, R.; Patel, D.; Mishra, S.; Kumar, V.; Singh, A. and Tiwari, P. (2025). Antidiabetic effects of garlic. Phytotherapy Research, **39**:85-102.

Tang, L.; Chen, X. and Wang, Y. (2025). Garlic and hypertension clinical trials. Clinical Nutrition Reports, **12**:88-95.

Thakur, P.; Sharma, D.; Singh, R. and Kumar, A. (2024). Bio-functionality of garlic and its compounds. Food Science Reviews, **12(2)**:88-102.

Tripathy, S.; Behera, T. K.; Das, S.; Mohapatra, P. and Mishra, S. (2025). Garlic breeding advances. Scientia Horticulturae, **325**:112345.

Tudu, C. K.; Dutta, T.; Ghorai, M.; Biswas, P.; Samanta, D. and Oleksak, P. (2022). Traditional uses, phytochemistry and pharmacology of garlic. Trends in Food Science and Technology, **119**:64-75.

Wiley, J.; Smith, A. and Brown, P. (2025). Industrial applications of garlic. Journal of Food Science, **90(5)**:2345-2356.

Yadav, S.; Kumar, A.; Singh, B.; Meena, R. and Sharma, G. (2023). Agronomic practices of garlic. Indian Journal of Horticulture, **80**:234-241.

Yousaf, R.; Shahid, S. and Iftikhar, M. (2025). Garlic antimicrobial studies. Journal of Applied Microbiology, **129**:145-156.

Zhao, Q.; Liu, J. and Sun, R. (2025). Garlic signaling pathways. Molecular Biology Reports, **52**:4567-4578.

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